FACULTY OF INFORMATION TECHNOLOGY AND ELECTRICAL ENGINEERING
DEGREE PROGRAMME IN ELECTRONICS AND COMMUNICATIONS ENGINEERING

MASTER'S THESIS

WIRELESS SETUPS FOR IMPROVED REMOTE AREA CONNECTIVITY

Author	Sanjeev Singh
Supervisor	Adj. Prof. Harri Saarnisaari
Second Examiner	Timo Kumpuniemi

June 2021

Singh S. (2021) Wireless setups for improved remote area connectivity. The University of Oulu, Faculty of Information Technology and Electrical Engineering, Degree Programme in Wireless Communications Engineering. Master's Thesis, 54 p.

ABSTRACT

This thesis considers the problem of low radio frequency (RF) signal strength at remote locations where connectivity has been proven to be problematic. In such areas, the low signal strength makes it more difficult for the residents to establish reliable internet connections. Moreover, in addition to long distance between mobile user and the base station the signal is degraded due to natural obstacles such as hills or forests. The most straightforward solution to the signal deterioration in this case is both elevating user's antenna and amplifying the received signal by means of dedicated devices. In this regard, we have proposed two configurations for improving the signal strength. The former one, described as fixed installation is installed at home. The elevated modem with the antenna together with the integrated router were used in order to facilitate proper reception for home-dwellers. The latter one, is referred to as semi-mobile installation, where the directional antenna is mounted on the vehicle in order to enable connectivity for users on the go. The measurement campaign was conducted at remote locations in Loppula and Rokua, Finland. The targeted long term evolution (LTE) signal was measured at band 20 at 800 MHz. In case of semi-mobile installation the performance of the inductive coupler was measured in terms of signal parameters received signal strength indicator (RSSI), reference signal received power (RSRP), reference signal received quality (RSRQ) and signal-to-noise ratio (SNR). For the fixed installation, the modem performance was measured in terms of data rate. In both cases, the installed set-up improved the quality of the signal, and thus can be recommended for users facing connectivity issues at remote locations.

Keywords: RF signal, remote connectivity, band 20, wireless solutions, inductive coupler, modem.

TABLE OF CONTENTS

FOREWORD

The thesis work is culmination of my master's study in wireless communication at University of Oulu. I finally carried out the thesis project but succeeding the thesis would have not been possible without the immense cooperation, encouragement and support of many people in my surroundings. The job of the thesis understanding and writing was one of the challenging tasks for me during this pandemic but I kept myself motivated and advanced with the clear intent to accomplish it.

I would like to sincerely thank to my thesis supervisor Adj. Prof. Harri Saarnisaari for his great guidance, advise and support throughout the thesis writing and data measurement. His valuable support helped me to move forward and follow the right path toward goal achievement. He always encouraged me to dig out information for my knowledge growth.

My sincere thanks also go to my technical advisor, Timo Kumpuniemi for his enormous theoretical and practical support in realising thesis writing and measurement task. I would like to thank Ville Niemelä for his technical role in supporting software and hardware devices needed for my thesis measurement.

A huge thank also goes to my friend Krishna Joshi who helped me technically for setting up measurement devices and record the measurement data. I appreciate for his unconditional help and friendly gesture.

I gratefully dedicate this thesis work to my parents who allowed me to travel thousands of miles to pursue my master's degree. I am equally thankful for my elder and younger brothers for their role in inspiring me during the course of my master's study.

Oulu, 23rd June, 2021

Sanjeev Singh

LIST OF ABBREVIATIONS AND SYMBOLS

2G	Second generation
4G	Fourth generation
5G	Fifth generation
eNB	Evolved node B
HF	High frequency
ID	Identification
IoT	Internet of things
LPDA	Log-periodic dipole array
LTE	Long term evolution
MIMO	Multiple input multiple output
NLoS	Non-line-of-sight
NSA	Non-standalone
OFDM	Orthogonal frequency division multiplexing
QoS	Quality of service
RE	Resource element
RG	Radio guide
RF	Radio frequency
RFID	Radio frequency identification
RSRP	Reference signal received power
RSSI	Received signal strength indicator
RSRQ	Reference signal received quality
SA	Standalone
SINR	Signal to interference plus noise ratio
SMA	Sub-miniature version A
VNA	Vector network analyser
VSWR	Voltage standing wave ratio
UE	User equipment
UHF	Ultra high frequency
UN	United Nations
Wi-Fi	Wireless fidelity
WiMAX	Worldwide interoperability for microwave access

A_e	Effective antenna area
B	Gain in antenna back beam
c	Speed of light
D	Directivity
D_0	Maximum directivity
f	Frequency
F	Gain in antenna main beam
f_{sw}	Switching frequency
G	Gain of antenna
k	Design ratio
K_Φ	Coupling factor
l	Length of dipole
L	Inductance

L_r	Length of reflector
L_P	Length of driven element
L_d	Length of director
L_1	Length of coil at transmitter
L_2	Length of coil at receiver
M	Mutual inductance
m	Meter
N	Number of elements in antenna
P_e	Eddy current loss
P_h	Hysteresis loss
P_{rad}	Total radiated power
P_{input}	Input power to the antenna
R_r	Radiation resistance
R_l	Loss resistance
R	Distance between feed and dipole
S_{rd}	Spacing between reflector to dipole
S_{dd}	Spacing between directors
T_x	Transmitter
U	Radiation intensity
U_{max}	Maximum radiation intensity
U_0	Radiation intensity of isotropic source
V	Voltage
Z_{in}	Input impedance
Z_{out}	Output impedance
λ	Wavelength
η	Total antenna efficiency
ΔB	Flux excursion
ρ	Resistivity of the material
Γ	Reflection coefficient

dB	Antenna gain or directivity in decibels
dBi	Antenna gain in decibels relative to the isotropic radiator
dBm	Power in decibels relative to one milliwatt
GHz	Gigahertz
MHz	Megahertz
THz	Terahertz

1 INTRODUCTION

The number of users communicating via cellular signal is growing worldwide [1]. The radio frequency signal is used for establishing the communication link between the transmitter and the receiver. The factors that are driving users dependence on cellular communication are globalization, digitization and the urbanization [2]. The communication links between the transmitters and receivers over distance are either the wired or the wireless links. The wired communication links are highly reliable but this mode of communication cannot be made available everywhere due to limitations like complex geography and remoteness. Thus the wireless mode of communication is a crucial option and increasingly gaining popularity for rural areas access network [3]. Over three billion of world population live in rural areas as stated in United Nations (UN) report [4]. Providing the connectivity for the populations living in the rural area is very challenging [5]. To realise good cellular signal connectivity, the infrastructure installation is important. The coverage of cellular connectivity in remote is comparatively low due to insufficient infrastructure and geographical sparsity of users [6].

There are challenges faced by radio frequency (RF) signals when they travel from the base stations to receivers in remote areas. The signals from the base station to the receiver reach either in line-of-sight (LoS) or non-line-of-sight (NLoS) path. The RF signal received by receivers at LoS range has good strength but also the long distance to the base station forms a problem. The RF signals to the receivers through NLoS paths are attenuated and are comparatively weaker in signal strength [7]. The attenuation is caused by factors such as reflection, refraction and scattering of RF signals. Similarly, the signals travelling from the base station to the other side of the hill get its strength attenuated due to shadowing or signal blockage [8]. It is the reason for any measurement device which displays low signal level on the opposite side of the hill. The low strength RF signal has the impediment in quality of communication between users. Such signals are quite unreliable in making the uninterrupted connection between the base station and the users. Even if the connection is available, the quality of service (QoS) is inferior. Internet service with the low signal strength takes a long time to send or receive information and voice calls are heard distorted. These RF signals need enhancement to ensure quality communication.

There are numerous technologies available such as the cellular, wireless fidelity (wi-fi), the hybrid broadband access network etc for increasing the connectivity to rural areas [3]. These technologies have their own advantages or disadvantages in terms of cost, QoS, availability etc. Nonetheless, the prime intentions of these technologies are to boost the signal strength and upgrade the quality of the networking service in rural areas. There are various networking devices that have been developed to ensure the weak signal strength. The devices are the directional antenna, modem integrated with wi-fi router etc. Directional antenna perform the crucial role in amplifying signal level. The directional antenna receives weak signals and is capable of providing significant gain. Another important device is the antenna cable which is an interface between the antenna and modem. Increasing signal strength also necessitates to reduce the loss occurring in the networking system. In common practice, low loss coaxial cables are used to transport the RF signal. This cable ensures very minimum loss in signal flowing through it. Similarly, the modem and wi-fi modem devices have inbuilt high gain antennas to pick weak signals and raise its strength.

1.1 Remote RF signal connectivity

The population in remote areas are distributed across various terrain. These populations have different motivation and purpose to live or travel there temporarily or permanently. Remote areas are the places where people sometime struggle for basic amenities. These remote locations could be the national park, hiking trails, villages, summer cottages, remote road links etc where people often travel for spending holidays, do research activities, hiking etc. These places may have complex geography, big hills, large trees etc which act as obstacles to the proper cellular signal connectivity. Base stations in remote locations often lies long distance apart and the direct signal connection to the receiver is hindered by hills and mountain. These natural obstructions attenuate the signal and the receivers are either cut off from the signal or get a weak signal.

The remote area connectivity issues cannot be ignored because these are the destinations of holiday spenders, hikers, researchers who spend weeks exploring these areas. Also, there are people who live there and work from remote. There are occasions when these group of people want to share crucial information, images, seek immediate medical help etc. The reliable cellular connectivity helps them meet their needs. The signal connectivity at rural areas may be weak but its strength can be raised. There are practical solutions which are reliable and benefit people living in remote. The solutions have advantages in establishing the reliable link.

1.2 Scope of the thesis

The weaker RF signal connectivity hampers quality communication at the remote locations. The installation of multiple base stations at these locations are not feasible physically and economically. Instead, today we have several solutions available to boost the signal strength. This thesis is oriented to measure the performance of network devices and recommend the devices for better rural connectivity. The remaining of the thesis is organized as follows. In Chapter 2, the use cases of the proposed signal enhancer devices are mentioned. Chapter 3 basically concerns the general information about the network devices. Chapter 4 deals the description of the signal parameters and the networking devices and applications that are used for signal measurement. Chapter 5 presents the measured data of this thesis. Analysing results are very significant after measurement and it is presented in Chapter 6. Chapter 7 contains discussion of the measurement and results. Chapter 8 draws the conclusion of the thesis measurement.

2 TARGET SYSTEM

The focus of the thesis is to improve RF signal strength installing signal booster devices in the remote areas where RF signal reception is relatively weak. The weak signal reception is often caused by the barriers like trees or hills between the transmitter and the receiver. It also depends on the distance between the transmitter and the receiver and the receiver position inside or outside of focused signal beam. The methods of improving weak signal strength is necessary and can be explained by the help of Fresnel zone concept which is illustrated in the figure 1.

There are several Fresnel zones created between the transmitter and the receiver. These Fresnel zones help to identify where the obstacles cause addition attenuation. To maximize the signal strength, it is necessary to minimize the effects of obstacles in the wave propagation path. If the obstacle is cleared, the propagation path is considered a LoS path. According to the rule of thumb, the first Fresnel zone is 60 percent clear of obstacles and has maximum signal strength [9].

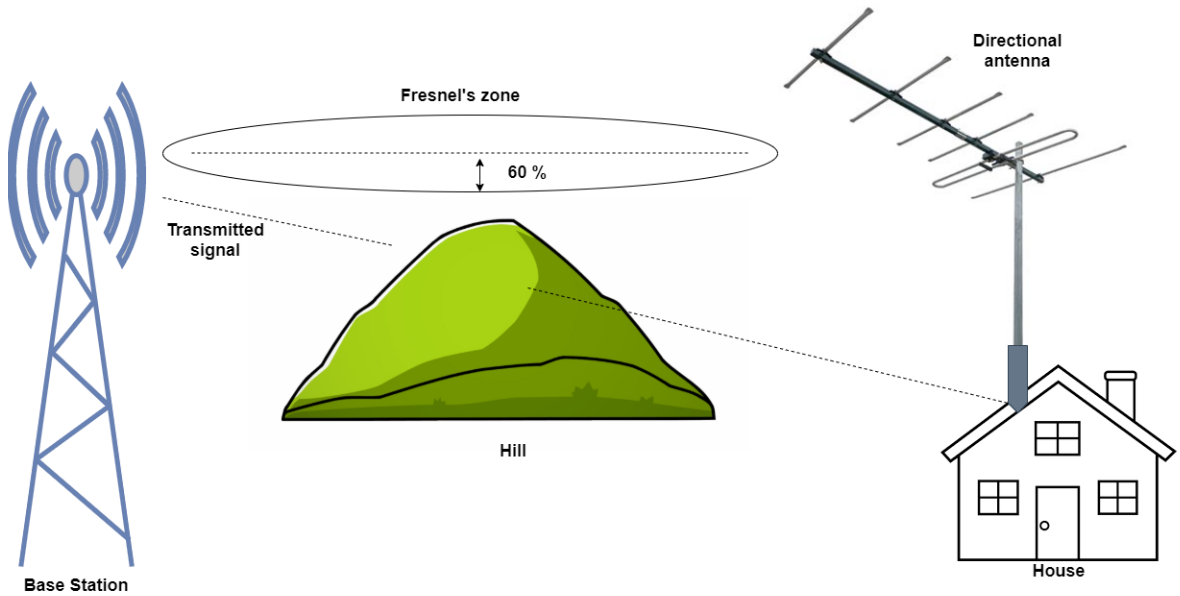

Figure 1. Illustration of Fresnel zone.

In the figure 1, the hill between the transmitter and the receiver hinders the direct reception of the RF signal. The received signal at far distance at this state is relatively weak. To enhance the signal strength, the directional antenna is installed at the house roof with the help of the mast. The directional antenna is able to pick weak signals from far distance and provide certain signal gain. In this sense, the directional antenna behaves as signal amplifier. The gain of the directional antenna depends on the type of antenna used. The height factor also plays a crucial role in strengthening the cellular signal. At certain height, the directional antenna aligns at LoS zone and thus receives the direct RF signal unhindered from the transmit base station.

2.1 Use cases

The reception of the better signal is possible through the installation and adoption of technology. There are methods of boosting the weak RF signals at remote destinations. We have identified two possible use cases. One is fixed installation type and another is semi-mobile installation type.

2.1.1 Fixed installation

Fixed installations are the installations which cannot be changed or moved unless there is some major modification to dismantle it. The example of fixed installation include houses, offices, stores etc. These are the type of installations which are used by people for long-term use. In the rural areas, fixed installations are the perfect spots where the directional antennas are installed. In common practice, highly directional antennas are mounted on the mast and installed on the house roof top. The mast is a metal or non-metal structure that support antenna in telecommunication. The mast itself does not take part in communication. This antenna thus installed is capable of picking up RF signal and provide large gain thereby increasing signal strength. The typical configuration of fixed installation is depicted in the figure 2.

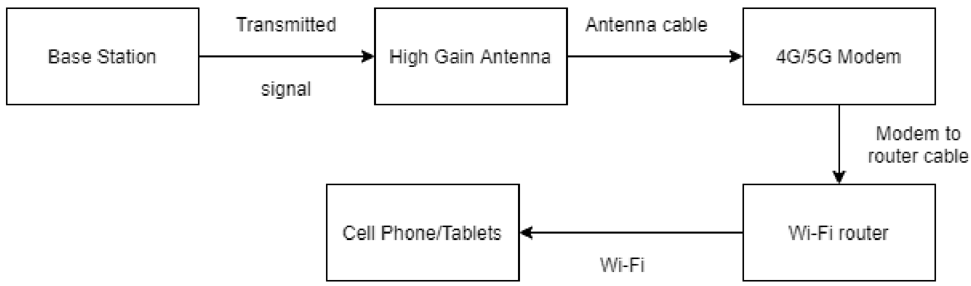

Figure 2. Fixed installation configuration.

In the fixed installation configuration, there is a base station, high gain antenna, 4G/5G modem with integrated router and end devices like cell phones and tablets as shown in the figure 2. The base station transmits the cellular signals needed for mobile communication. The cellular signal also called RF signal is an electromagnetic signal which carries information for cellular communication. This RF signal is picked by the directional antenna which is capable of boosting the signal level. The directional antenna sends the boosted RF signal to the modem through the low loss coaxial cable. The coaxial cable is used for RF signal transmission and its length is chosen as short as possible in order to minimize the signal transmission loss. The cable with higher signal attenuation is undesirable because it affects the gain and overall performance of the configuration. The modem behaves as a transducer which translates incoming analog data into digital data and converting digital data into analog data. The received RF signal is the cellular LTE signal which is converted into the digital format by the modem. The digital signal from the modem is fed to the router. The router is a networking device that aids connecting a local home network and the internet. The local home network includes computer, cell phones and other electronic devices. An example is a wi-fi router which gets the signal from the modem through modem-to-router cable. Both options can be practically used to enhance the signal strength in remote installations.

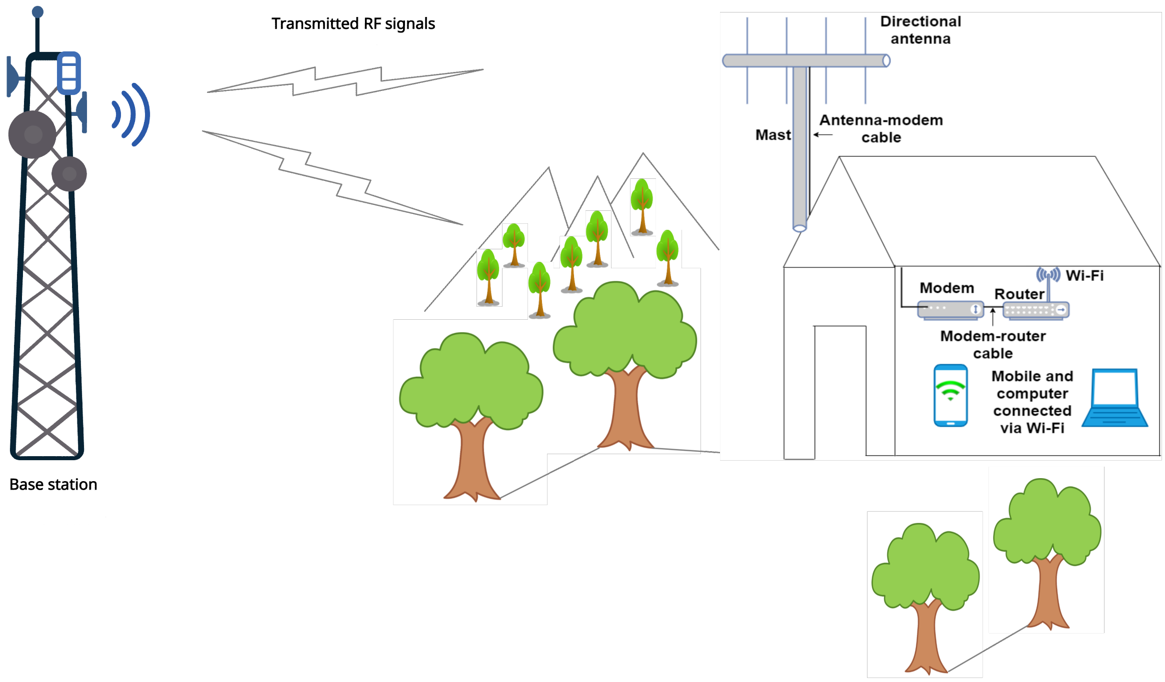

Figure 3. Demonstration of fixed indoor installation.

The figure 3 shows the real life application of fixed installation in remote areas. In this configuration, the RF signal, measured in decibels relative to one milliwatt (dBm) from the base station is received by the directional antenna. The directional antenna has properties to provide large gain and the gain depends upon design of the directional antenna. So, the directional antenna enhances the signal strength and provides gain measured in decibels (dB). The signal then travels to the modem and the router through antenna-to-modem and modem-to-router cables, respectively. The router then converts the digital signal to wi-fi which is used to connect end devices like a cell phone. The cables used in this use case are minimum signal loss cables and their losses are measured in dB. The signal strength at the receiver can be expressed as

Signal strength at receiver = original signal strength received by antenna in dBm + gain enhancement by antenna in dB - losses in cable in dB.

Other notable factor that affect signal reception at remote areas is the height of the mast. Proper selection of mast height allows the directional antenna to receive RF signal directly from the base station. The proper selection of mast height also avoids signal losses caused by barriers like trees or buildings. While choosing the height of the mast, it should be noted that the length of cable connecting directional antenna and modem also increases. Since the loss in the cable is also function of length [10], cable loss increases with cable length. Cable loss also varies with manufacturing technology and quality.

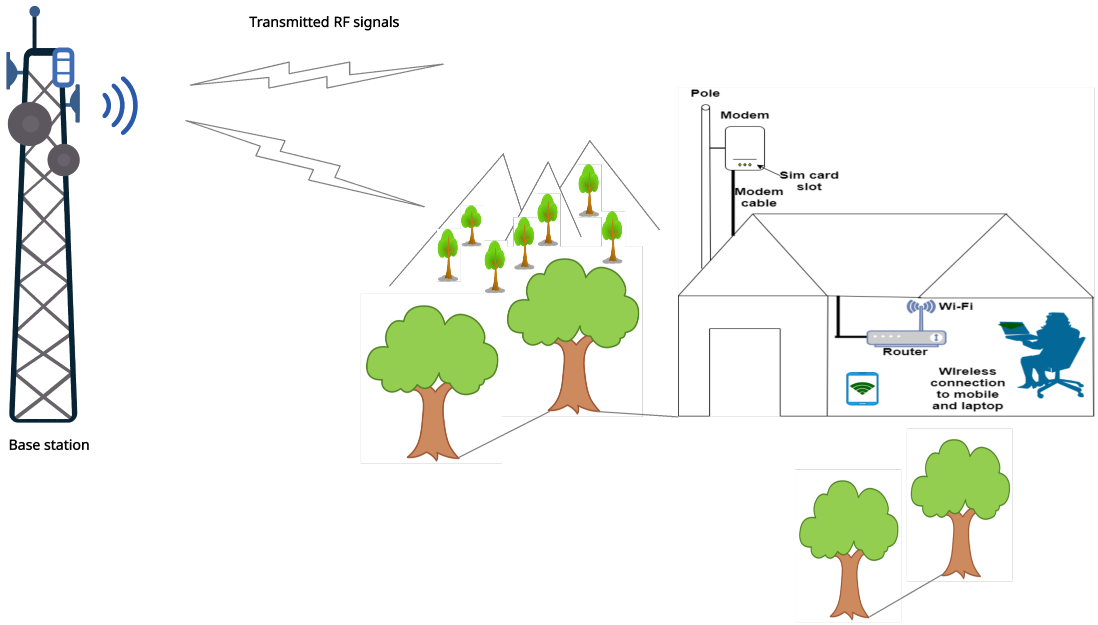

Figure 4. Demonstration of fixed outdoor installation.

It is also possible to install modem outdoor on roof top with the help of the mast as shown in the figure 4. The router depicted in this configuration provides high quality signal reception and transmission and it is able to increase the speed of 4G and 5G mobile internet. The router is laced with MIMO antenna technology thus there is diversity of signal transmission and reception. This router provides internet connectivity via wi-fi and cable connection. Overall, this router has advantage of enhancing signal strength, supporting 4G and 5G services over wide ranges of frequencies and has the omnidirectioal antenna for home application. It is small in size and easy to install at home.

2.1.2 Semi-mobile installation

Another possible use case is semi-mobile installation. Semi-mobile installation is applicable when users are wandering, doing some research activity, hiking or rescuing affected people in remote location where signal strength is low. In this installation, a phone-to-antenna adapter is used to boost the signal connectivity and better communication as shown in the block diagram figure 5.

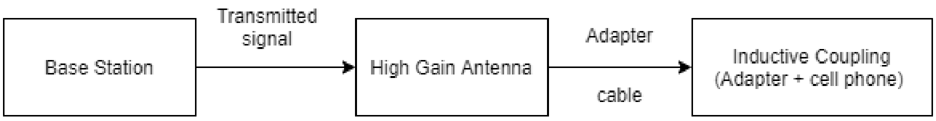

Figure 5. Semi-mobile installation.

An example of semi-mobile application is shown in the figure 6. Weak signal strength hampers the quality communication but proposed usecase e.g, semi-mobile installation can be adopted for better data communication. People can mount the directional antenna on the vehicle with the help of the mast. The antenna is connected to phone-to-antenna adapter via low loss adapter cable. The cell-phone is placed against the adapter which is small in size, handy and acts as the miniature cell tower [11]. The cradle booster is another device which can be fixed and used inside the car. It acts as an antenna and cell phone attached to it is able to get the strong signal. The advantage of this type of installation is that it is portable, easy to install and is the effective solution to the fast internet connection.

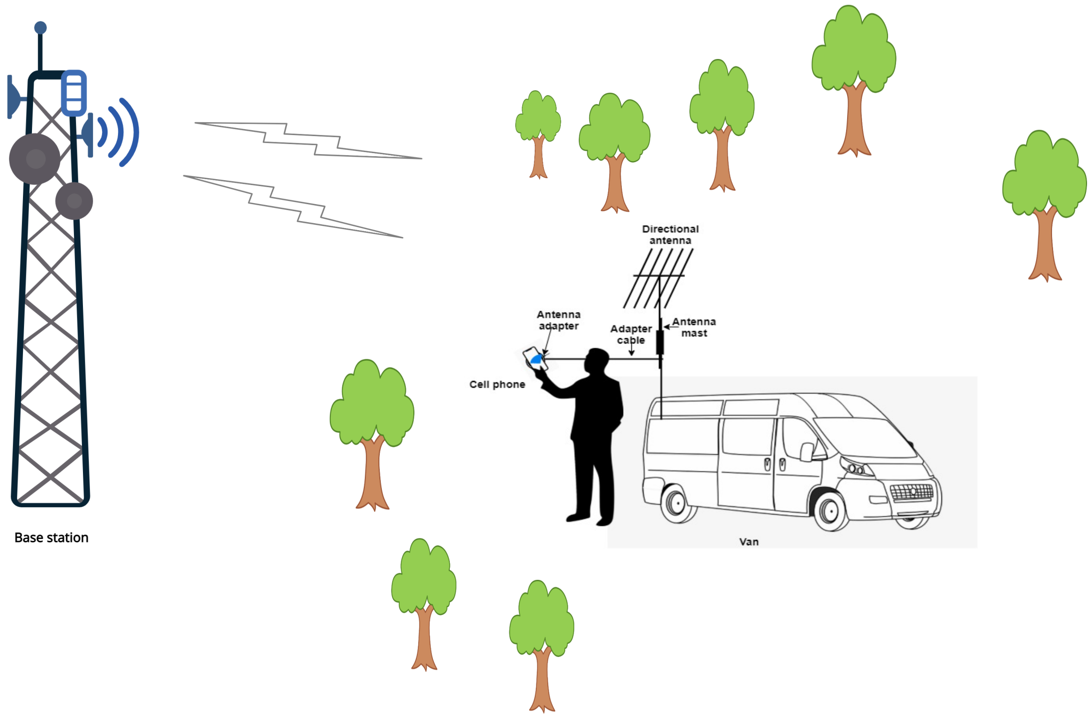

Figure 6. Demonstration of semi-mobile installation.

3 BACKGROUND

3.1 Antenna basics

The antenna is a transducer that converts electrical signals into electromagnetic waves and vice-versa. The antenna is usually a metallic device which can radiate or receive radio waves [12]. Antennas have varieties of shapes and have different applications. Antennas are divided into various types depending on its physical structure, frequency ranges of operation and mode of antenna applications. The performance of the antenna is defined by some basic parameters which are described below.

Gain: Gain is actually the measure of the antenna ability to focus the radiated power in a particular direction. The directional antenna is a high gain antenna and radiates power in a specific direction. The gain of the antenna is usually referenced to an isotropic antenna, which emits the radiation evenly strong in all directions. A receiving antenna with 3 dBi gain in the specific direction means that the antenna would receive 3 dB more power than a lossless isotropic antenna. The gain of the antenna is measured in dBi (antenna gain in decibels relative to the isotropic radiator). Mathematically, the antenna gain is written as

$$\mathrm{G} = \frac{4\pi \mathrm{A_e}}{\lambda^2} = \frac{4\pi \mathrm{f}^2 \mathrm{A_e}}{\mathrm{c}^2}, \tag{1}$$

where

$\mathrm{A_e}$ = effective antenna area,
λ = wavelength,
f = frequency of wave,
c = speed of light (3×10^8m/s).

The gain of the antenna is dependent on the frequency and aperture area of the antenna as shown in the equation 1. Gain is directly dependent on frequency meaning the increase in frequency increases the gain of the antenna. The gain of an antenna also increases if the effective antenna area is large.

Directivity: Directivity is considered the fundamental parameter of the antenna which measures how directional an antenna radiation pattern is in the particular direction [13]. Therefore, the directivity of an antenna is defined as the ratio of antenna radiation in the specific direction to the radiation intensity averaged from all directions [12]. The average radiation intensity is further given as total power radiated by the antenna divided by 4π. Antenna with higher directivity radiates the focused beam in the specific direction while the antenna with lower directivity fails to focus the radiation beam in the specific direction. The omnidirectional antenna has a doughnut shaped radiation pattern and its directivity is considered one. On the contrary, highly directional antenna directs radiated power in the specific direction. The unit of measurement of directivity is dBi. Highly directed rays also travel farther distance. The radiation pattern of the directional antenna e.g, the Yagi-Uda antenna consists of the major lobe directed in one direction and minor lobes which have insignificant radiation pattern. The minor lobes are suppressed and the directivity of the antenna is further increased by the addition of the directors. In mathematical notation, the radiated power is written as

$$\mathrm{D} = \frac{\mathrm{U}}{\mathrm{U}_0} = \frac{4\pi \mathrm{U}}{\mathrm{P}_{\mathrm{rad}}}, \tag{2}$$

if the direction is not mentioned then maximum direction of intensity is expressed as

$$\mathrm{D}_{\mathrm{max}} = \mathrm{D}_0 = \frac{\mathrm{U}_{\mathrm{max}}}{\mathrm{U}_0} = \frac{4\pi \mathrm{U}_{\mathrm{max}}}{\mathrm{P}_{\mathrm{rad}}}, \tag{3}$$

where

D = directivity (dimensionless),
D_0 = maximum directivity (dimensionless),
U = radiation intensity (W/unit solid angle),
$\mathrm{U}_{\mathrm{max}}$ = maximum radiation intensity (W/unit solid angle),
U_0 = radiation intensity of isotropic source (W/unit solid angle),
$\mathrm{P}_{\mathrm{rad}}$ = total radiated power (W).

Antenna efficiency: Antenna efficiency is the ratio of the total radiated power of the antenna to the input power accepted by the antenna [9]. The efficiency signifies the amount of power radiated by the antenna in the transmission line with low losses. The antenna with high efficiency has most of its power present at antenna's input which is radiated away. Similarly, the antenna with low efficiency has power absorbed or reflected away due to impedance mismatch in the antenna circuit. In the mathematical form efficiency, η can be written as

$$\eta = \frac{\mathrm{P}_{\mathrm{rad}}}{\mathrm{P}_{\mathrm{input}}} = \frac{\mathrm{R}_{\mathrm{r}}}{\mathrm{R}_{\mathrm{r}} + \mathrm{R}_{\mathrm{l}}}, \tag{4}$$

where

η = antenna efficiency,
$\mathrm{P}_{\mathrm{rad}}$ = total power radiated,
$\mathrm{P}_{\mathrm{input}}$ = input power to the antenna,
R_{r} = radiation resistance,
R_{l} = loss resistance.

The antenna in the ideal case has 100 percent efficiency, but this type of antenna is hard to achieve. In practice, the efficiency of the antenna is less than in the ideal case. The antenna with high efficiency is preferred but losses like conduction losses, impedance mismatch, dielectric losses degrade the total performance of the antenna. Impedance mismatch causes reflection of the signal between transmission line and antenna [12]. When the impedance is matched then maximum power is delivered to the antenna. The impedance mismatch is measured by reflection coefficient and is defined by

$$\Gamma = \frac{\mathrm{Z}_{\mathrm{in}} - \mathrm{Z}_{\mathrm{out}}}{\mathrm{Z}_{\mathrm{in}} + \mathrm{Z}_{\mathrm{out}}}, \tag{5}$$

where

Γ = reflection coefficient,
Z_{in} = input impedance,
Z_{out} = output impedance.

The mismatch is also commonly measured through voltage standing wave ratio (VSWR) and is given as

$$\mathrm{VSWR} = \frac{1+|\Gamma|}{1-|\Gamma|}, \tag{6}$$

Front-to-back ratio: Front-to-back ratio is a parameter which describes the radiation pattern of the directional antenna. It is a ratio of power gain between the main lobe and the back lobe of the directional antenna. In other words, front-to-back ratio is a ratio of signal strength propagated in the forward direction to that of signal strength directed in the backward direction. The front-to-back ratio parameter is usually given in dB. The directional antenna radiation pattern consists of the main lobe and the back lobe where the main lobe is always dominant over the back lobe. This domination of the main lobe in the specific direction illustrates the high front-to-back ratio. This ratio also compares antenna gain in the particular direction. In mathematical term, front-to-back ratio is written as

$$\mathrm{Front-to-back\ ratio} = \frac{\mathrm{F}}{\mathrm{B}}, \tag{7}$$

where,

F = gain toward main lobe,
B = gain toward back lobe.

In practice the high performance antenna has the higher front-to-back ratio. It is a necessary parameter for the antenna where the interference or coverage in the back lobe need to be minimised.

3.2 Yagi-Uda antenna

Yagi-Uda antenna invented in 1926 by Shintaro Uda of Tohoku imperial university, Japan along with his colleague Hidetsugu Yagi is a directional antenna that radiates the radio signal in one direction. The basic configuration of Yagi-Uda antenna consists of the single reflector, feeder connected to long transmission line and a number of parasitic elements known as directors [14]. The reflector is placed left to the driven element and its length is slightly longer than the driven element. The main purpose of the reflector is to direct the signal coming form the driven element toward directors. The feeder also known as driven element is the half wave dipole antenna where the input signal is fed. The driven element emits the electromagnetic wave which is directed in one direction by the directors attached in parallel to the drive element. The length of the directors gradually decreases in the right direction of driven element. The typical Yagi-Uda antenna structure is shown in the figure 7 and is referenced from the book [12].

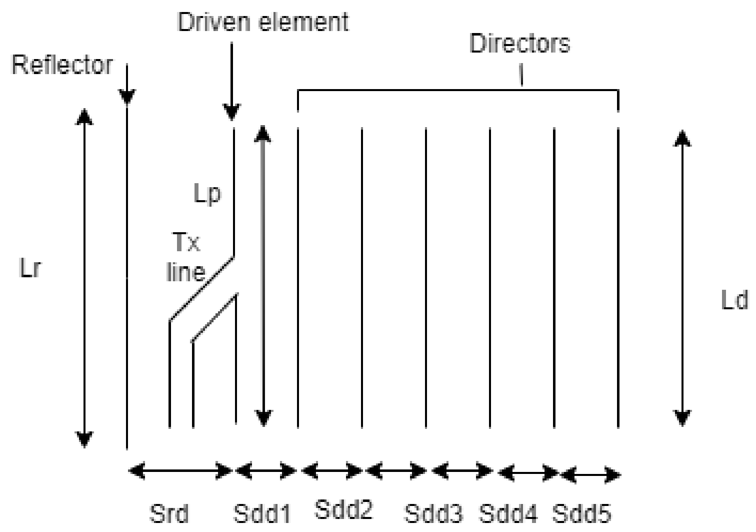

Figure 7. General Yagi-Uda antenna structure.

Yagi-Uda antenna is very popular for its directivity and gain. It is mainly used for television signal reception but it has other major commercial and domestic applications [15]. It helps in the reception of the signal from the specific direction. Yagi-Uda antenna is designed to operate in the high frequency (HF) and ultra-high frequency (UHF) frequency range i.e 3 MHz to 3 GHz. Yagi-Uda antenna has three main elements namely, the director, dipole and reflector. The proper selection of these elements lengths, their numbers and their spacing in an antenna configuration determines the effectiveness of the antenna in terms of gain and directivity [16]. The dipole is energized with feed transmission line and the currents are induced in the parasitic elements through mutual coupling. Reflector and director are the parasitic elements because they redirect radiation emitted from dipole to a particular direction. The redirection of the radiated wave depends upon the length and spacing between the parasitic elements and dipole. Generally, the length of reflector (L_r) is greater than the resonant length i.e greater than dipole, and it displays inductive property. In this case, the current in the reflector lags the voltage induced on the reflector. Generally, in Yagi-Uda antenna design, only one reflector is considered and its length is 5 percent more than the dipole. Similarly, the lengths of the directors are shorter and a Yagi-Uda antenna may consists of multiple directors. The dipole directors exhibit capacitive property thus current leads the voltage and add gain in the forward direction. The phase distributions occur across the antenna elements and leads to phase progression across the array elements. In this way, Yagi-Uda antenna becomes an end-fire array.

The gain of Yagi-Uda antenna depends on factors like dipole gain and the element attached with the configuration [17]. The gain is given as

$$G = 1.66N, \tag{8}$$

where

$1.66 =$ dipole gain,

N = number of elements in antenna.

The gain of the Yagi-Uda antenna increases with the rise in the number of the directors.

The length of the reflector (L_r), driven element (L_p) and directors (L_d) also depends upon the frequency used for the propagation of the radio wave. Due to the antenna ability to provide high gain in the given direction, the Yagi-Uda antenna produces narrow frequency range. The typical bandwidth of Yagi-Uda antenna is about 10 percent form the operating frequency [12]. The Yagi-Uda antenna has the array of parallel elements attached to the substrate called the boom as shown in the figure 7. The length of dipole attached to the boom is slightly less than $\lambda/2$. The length of the reflector is slightly greater, about 5 percent more than dipole's length. Similarly, the lengths of the directors are between 0.4λ to 0.45λ. The spacing between the reflector to dipole (S_{rd}) is nearly $\lambda/4$ and the spacing between the directors (S_{dd}) are between 0.2 to 0.4λ.

The directional antenna used for frequency measurement range from 700 MHz to 3.5 GHz. Let us first consider the lowest frequency 700 MHz for the Yagi-Uda antenna design. Then the specification for the elements of Yagi-Uda antenna would be.

$$\lambda = \frac{\mathrm{c}}{\mathrm{f}} = \frac{3 \times 10^8}{700 \times 10^6} = 0.428 \text{ m}. \tag{9}$$

For frequency 700 MHz, the length of the Yagi-Uda antenna elements are calculated using the formula listed below in the table 1

Table 1. Antenna element length calculation at 700 MHz.

Elements	**Formula**	**Calculated length**
Reflector	$0.54 \times \lambda$	$0.54 \times 0.428 = 0.23112$ m
Dipole	$0.49 \times \lambda$	$0.49 \times 0.428 = 0.20972$ m
Director1	$0.45 \times \lambda$	$0.45 \times 0.428 = 0.1926$ m
S_{rd}	$0.1 \times \lambda$	$0.1 \times 0.428 = 0.428$ m
S_{dd1}	$0.1 \times \lambda$	$0.1 \times 0.428 = 0.428$ m

Similarly, for the frequency 3.5 GHz, the carrier wavelength is

$$\lambda = \frac{\mathrm{c}}{\mathrm{f}} = \frac{3 \times 10^8}{3.5 \times 10^9} = 0.085 \text{ m}. \tag{10}$$

At this frequency, the length of the antenna elements is calculated as illustrated in the table 2.

Table 2. Antenna element length calculation at 3.5 GHz.

Elements	Formula	Calculated length
Reflector	$0.54 \times \lambda$	$0.54 \times 0.085 = 0.0459$ m
Dipole	$0.49 \times \lambda$	$0.49 \times 0.085 = 0.04165$ m
Director1	$0.45 \times \lambda$	$0.45 \times 0.085 = 0.03825$ m
S_{rd}	$0.1 \times \lambda$	$0.1 \times 0.085 = 0.085$ m
S_{dd1}	$0.1 \times \lambda$	$0.1 \times 0.085 = 0.085$ m

3.2.1 Log-periodic antenna

Most common form of the log-periodic antenna is the log-periodic dipole array (LPDA) which has numbers of half-wave dipole driven elements of gradually increasing length. The dipoles are connected in parallel with alternating the phase. In electrical language, the log-periodic antenna literally simulates two or three element Yagi-Uda antennas connected together where each Yagi-Uda antenna is tuned to separate frequency [18].
The log-periodic antenna is one of the most popular and widely used antennas in wireless communication technology. The antenna is highly directional and provides high gain. The log-periodic antenna is a multi-element, directional narrow beam antenna which works on the wide range of frequencies. The antenna is constructed by placing series of dipoles along the axis maintaining the space interval of time and logarithmic function of frequency. The dipole size reduces from the back end to the front end and the leading beam of this antenna comes from the smaller front end. The log-periodic antenna is used for application where wide bandwidth, high directivity and gain are required.

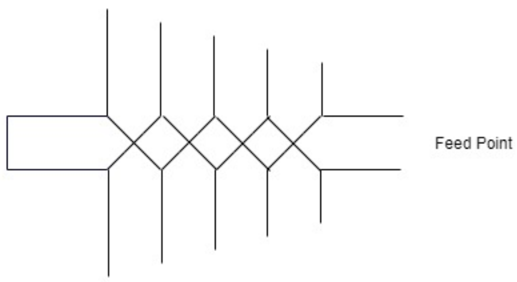

Figure 8. Electrical structure of log-periodic antenna [18].

In the figure 8, we see the general structure of the log-periodic antenna. The dipoles of the antenna are repetitive in nature. The dipoles of different length and structure are fed from the two wire transmission line. The lengths of the dipoles and spacing between them are given by the formula [18]

$$\frac{\mathrm{R}_1}{\mathrm{R}_2} = \frac{\mathrm{R}_2}{\mathrm{R}_3} = \frac{\mathrm{R}_3}{\mathrm{R}_4} = \mathrm{k} = \frac{\mathrm{l}_1}{\mathrm{l}_2} = \frac{\mathrm{l}_2}{\mathrm{l}_3} = \frac{\mathrm{l}_3}{\mathrm{l}_4}, \tag{11}$$

where

R = the distance between feed and dipole,
k = the design ratio and k<1,
l = length of dipole.

Though Yagi-Uda antenna gives high directivity and gain, the main drawback of this antenna is its limitation to provide wide bandwidth. The log-periodic antenna is replacement for Yagi-Uda antenna which provides wide bandwidth in addition to high directivity and gain. The log-periodic antenna is called periodic because its impedance is logarithamically periodic function of frequency.

3.2.2 MIMO cross-polarization antenna

Multiple input multiple output (MIMO) is an antenna technology that uses the multiple transmit and the receive antennas for radio signal transmission and reception [19]. MIMO technology offers high speed, improved range and high reliability [20]. In MIMO technology, the multiple receive antennas receive the same signal at different time instant. The signal travels different distances suffering fading and other losses. In MIMO, the probability that all the signals sent would be affected, is less. The output of the MIMO antenna configuration is the linear combination of the received signal.

Cross polarization is a concept where two waves are separated to each other by changing the polarization of the signal [21]. In the antenna, if the field is to be horizontally polarized then the cross-polarization in this situation is vertical polarization. MIMO cross-polarization antenna is the type of antenna which hold two or more Yagi-Uda antenna together attached to the mast at some angle. The antennas are tilted at some angle and works on the principle of MIMO. The cross polarization of the antenna introduces the concept of diversity. If one antenna in the configuration receive the faded or the weaker signal, then the other antennas in the same configuration would receive the stronger signal. These diversities of the antenna in cross polarization help to increase the signal quality and reliability. These antennas are useful for all 4G LTE frequencies. MIMO cross-polarization antenna consists of directional antennas which provide large gain. This antenna has ability to work on the large range of frequencies and provide the better data rate. The MIMO cross-polarization antenna is shown in the figure 9.

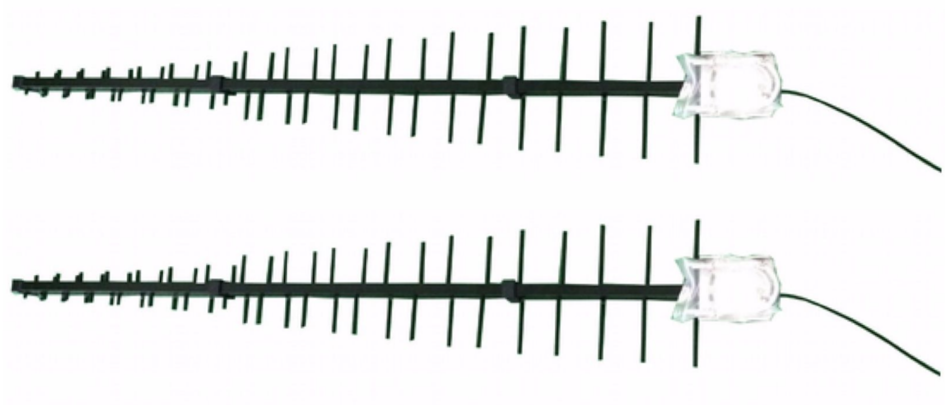

Figure 9. MIMO cross-polarization antenna [21].

Cross polarized antennas are suitable for MIMO applications, has wideband frequency coverage, the better front-to-back ratio, excellent polarization isolation and excellent reliability. It also provides better power and beamforming gain.

3.3 Antenna cable

The antenna cable is an electrical cable that is used to connect antenna and modem or any compatible electronic interface. Coaxial cables are the most commonly used antenna cables for signal transmission. The antenna cable transmits the signal between electronic devices and terminates with connectors at both ends. The design of the antenna cable consists of the inner conductor surrounded by insulation which is further surrounded by insulation and then aluminium tape binder. The copper wire braid shield follows the binder layer and finally the outer jacket layer. This coaxial cable is mainly used for transmission of high or low radio frequency signals over distances with low losses [22]. The antenna cable is popular for its quick signal transmission property and its resistance against external interference or environmental factors. The various types of cable used for the antenna connection are described below.

3.3.1 Cable types

There are several types of antenna cable which are used for the connecting antennas. Some of them are described below.

Hard-line coaxial cable: The hard-line coaxial cable is most commonly used type of RF coaxial cable which has the larger cable diameter than others. The center conductor of this cable is made of material like copper, aluminium or silver. The hard-line coaxial cable is used for long term installation and is capable of withstanding extreme climate and high voltages [23].

Semi-rigid coaxial cable: The semi-rigid coaxial cable is a cable that is applicable to the wide range of frequencies application. It is flexible and can be used for microwave application. It consists of the solid inner conductor surrounded by polymer layer and outer insulator layer [23]. This cable malleable and retain its shape if conformed. The example of this type of cable are RG 401, RG 405 etc.

Flexible coaxial cable: The flexible cables are the cable which can flex and move as required and easily fit the configuration and geometry of the application. This cable has the metal inner conductor surrounded by flexible dielectric and the outer jacket for protection from environment [23]. The flexible cable is used for high-speed wireless links. This cable is usually thin and flexible. The example of the flexible cable are RG 58, RG 174, RG 178 etc.

Low loss LMR cable: The LMR cable is a type of coaxial cable which has the low signal loss rate compared with the similar coaxial cable diameter. LMR cable consists of the solid inner conductor, high resistance dielectric, wire braid and foil shielding under the outer jacket. These layers contribute to the superior performance. The example of low loss LMR cables are LMR 100, LMR 195, LMR 200, LMR 400.

3.3.2 Cable losses

The RF signal passing through the transmission path dissipates some energy in the cable and attached components [24]. All antenna cables have some degree of signal loss which is determined by the cable type and its associated length. Cable loss generally refers to loss of the power over the given length of the cable. The term used for the cable loss is insertion loss and should be considered during the system design. Signal loss is less for shorter cable length and high for longer cable length [25]. The cable impedance is the important factor to be considered and is taken as 50 ohm for cellular devices. Cable loss is also dependent on introduced RF frequency.

The table 3 shows different types of cable technology and their losses at different frequencies. The cable losses are measured in decibels per metre (dB/m). The smaller the signal loss, the stronger the signal remains through the coaxial cable. The cable loss is an important factor to be considered when measuring the overall system performance. The most common cable technologies used are RG-174, RG-58U, LMR-240 and LMR-400 [21].

Table 3. Losses of some commercial cables in dB/m.

Loss per meter			
Cable type	**900 MHz**	**2.1 GHz**	**2.6 GHz**
RG-174	1.0 dB	1.8 dB	2.1 dB
RG-58U	0.39 dB	0.62 dB	0.71 dB
LMR-200	0.33 dB	0.50 dB	0.57 dB
LMR-400	0.13 dB	0.20 dB	0.23 dB

The table 4 compares the losses of two different cable types for length of 2 m, 5 m and 10 m. In this table, the LMR-400 cable has very less loss compared with RG-174.

Table 4. Comparison of cable losses at different length in dB/m.

Loss in dB			
Cable type	**2m**	**5m**	**10m**
RG-174	$1.0 \times 2 = 2$ dB	$1.0 \times 5 = 5$ dB	$1.0 \times 10 = 10$ dB
LMR-400	$0.13 \times 2 = 0.26$ dB	$0.13 \times 5 = 0.65$ dB	$0.13 \times 10 = 1.3$ dB

Hence, the signal strength after the comparison is stronger in LMR-400. When the signal is transmitted through the cable, some of its energy is lost in the cable and to associated components. The cable loss measurement is made at the installation phase to ensure that the cable loss is within manufacturer's specification. The cable loss measurement is made with a vector/scalar network analyzer or with a power meter. Cable loss can be measured using the return loss measurement available in the cable and antenna analyzer. By placing a short circuit at the end of the cable, the signal is reflected back and the energy lost in the cable can be computed [26]. The increase in RF frequency and the length of the cable increases insertion loss. The cables with large diameters have less insertion loss and better power handling capacity compared with the cable with the less diameter.

3.4 Passive inductance

Inductance is the tendency to oppose the flow of the electric current. Passive components such as inductor oppose the flow of the electric current in the circuit [27]. The inductor is basically a coil of wire as shown in the figure 10. When current is applied to the terminal of the coil, an electrical field is generated. The induced current is directly proportional to the length and number of turns in the coil. The current in the inductor lags voltage by 90 degrees [27]. Inductors can store energy in it as a magnetic field and can also deliver the energy to the circuit. This energy absorbing and delivering capacity is limited and transient in nature. Hence, the inductor is called passive element in the circuit [28]. Inductance is denoted by L.

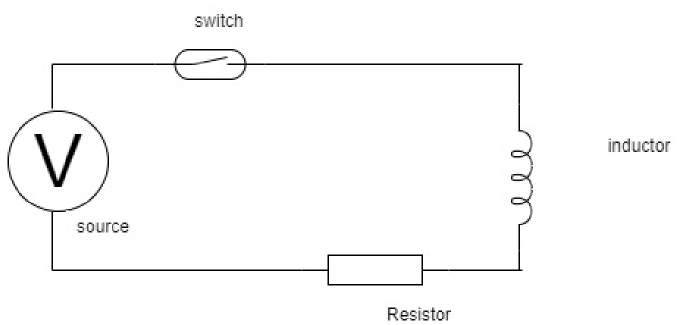

Figure 10. Inductor connection in circuit.

The inductance, L is the measure of inductor resistance to the rate of change of current flowing through that circuit. The rate of change of current will be lower for higher values of inductor and vice-versa. The inductance L is given as

$$\mathrm{L} = \mathrm{V}\frac{\mathrm{di}}{\mathrm{dt}}, \mathrm{Henry} \tag{12}$$

where

V = voltage applied,
$\frac{\mathrm{di}}{\mathrm{dt}}$ = rate of change in current.

3.4.1 Antenna couplers

The antenna coupler is a device which is connected between the antenna and the radio transmitter. The function of the coupler is to match antenna load to the transmitter and receiver for maximizing power transfer to the antenna [29].

3.4.2 Inductive coupling

Coupling is the transfer of energy from one medium to another medium. Inductive coupling uses near-field effects. In the inductive coupling, the energy is shared from one circuit component to another through a shared magnetic field [30]. A change in current flow through one device induces current flow in the other device. Inductive coupling favours low-frequency energy sources [31]. Inductive coupling is the near field wireless transmission of electrical energy between magnetically coupled coils, which is part of a resonant circuit tuned to resonate at the same frequency as the driving frequency. In other word, inductive coupling involves two wire configured in such a way that current flowing through one wire induces voltage across the ends of the other wire through electromagnetic induction as shown in the figure 11. It illustrates basic inductive coupling [32].

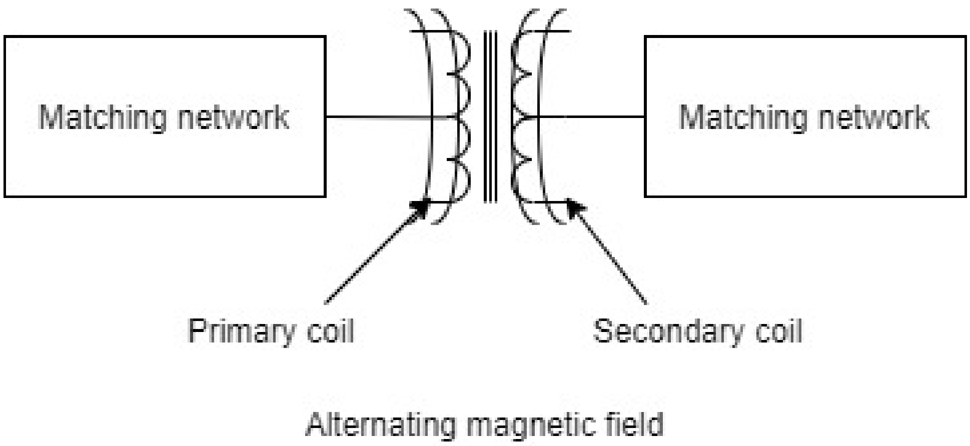

Figure 11. Inductive coupling.

From the figure 11, the inductive coupling link can be viewed as a transmitter inductor and receiver inductor which transfer energy by common variable field lines. We can write the mutual inductance between the coils as [30].

$$\mathrm{M} = \mathrm{K}_{\Phi}\sqrt{\mathrm{L}_1\mathrm{L}_2}, \tag{13}$$

where

M = mutual inductance,
K_{Φ} = coupling factor,
L_1 = length of coil at transmitter, and
L_2 = length of coil at receiver.

The coupling factor K_{Φ} is defined as the ratio of magnetic flux produced by the current in one coil that link with the other coil. The value of K_{Φ} for ideal condition is taken as 1 and given is by equation

$$\mathrm{K}_{\Phi} = \frac{\mathrm{M}}{\sqrt{\mathrm{L}_1\mathrm{L}_2}}, \tag{14}$$

3.4.3 Inductive coupling losses

Inductors are passive device and are not capable of generating the signal itself. Inductors are basically the coil with high resistance. When the electrical signal is fed to it, there is reduction in the original signal due to its resistance in the coil. There are power losses in the magnetic structure of inductive coupling. The losses associated with inductive coupling are described below.

Core loss: The core loss is the loss that occurs in the magnetic core due to changing magnetic flux [33]. Core losses constitute of eddy current and hysteresis losses. Eddy current is proportional to the square of the voltage applied and it is independent of frequency. On the contrary, the hysteresis loss is dependent on frequency applied. The hysteresis loss increases with the increase in the frequency. The state to remain magnetized is hysteresis. To eliminate this hysteresis, certain amount of energy is required every time when the field is applied. This hysteresis loss can be removed by choosing material with low hysteresis and designing the core with large area [34]. The hysteresis loss per unit volume is given as

$$\mathrm{P_h = kf_{sw}^a(\frac{\Delta B}{2})^d(W/m^3)}, \tag{15}$$

where

$\mathrm{k,\ a\ and\ d}$ = material related constant,
$\mathrm{f_{sw}}$ = switching frequency, and
$\Delta\mathrm{B}$ = is flux excursion.

Due to eddy current, current are induced in the core which circulates through the cross section of the core. This circulating currents resist electrical resistance which after is dissipated in the form of heat in the core. The eddy current can be reduced by choosing core material with low conductivity properties. The eddy current losses in volume is given as

$$\mathrm{P_e} = \frac{\mathrm{B^2 f_{sw}^2 d^2}}{\rho}\mathrm{(W/m^3)}, \tag{16}$$

where

$\mathrm{P_e}$ = eddy current loss,
ρ = resistivity of the material,
$\mathrm{f_{sw}}$ = switching frequency.

Conduction losses: Conduction loss always happens due to the flow of the signal through the conductor [35]. The loss thus incurred is dissipated in the form of heat. The conduction loss can be reduced by increasing the gauge of the coil.

4 PARAMETERS AND COMPONENTS DESCRIPTION

Before going to the actual measurement, it is necessary to define what parameters of the RF signal we are concerned with and what devices and components are required for the RF signal measurement. The components used for the measurements are all illustrated in the chapter 2 use cases.

4.1 RF signal parameters

Signal measurement parameters are the parameters which are used to measure the quality of LTE cellular signal. These parameters are the reference signal received power (RSRP), received signal strength indicator (RSSI), reference signal received quality (RSRQ) and signal to interference plus noise ratio (SINR). They are used to measure the signal level and quality in the modern radio communication network. These parameters are interconnected with each other and signal quality depends on all these parameters. A single reading of these parameters does not essentially mean that signal under measurement is good or bad. A good signal quality analysis is done on the basis of the analysis of all these four parameters. These parameter measurements are done by user equipment (UE) using proper measurement reporting applications. For example, mobile phone uses software like cellMapper to test cellular signal parameters. The signal quality measurement parameters are described below.

4.1.1 RSRP

RSRP is the average power of resource elements (RE) that carry cell specific reference signals over the entire bandwidth [36]. The resource element is one sub-carrier on orthogonal frequency multiple multiplexing (OFDM) signal in one OFDM symbol. RSRP is measured from symbols carrying reference signals (RS). RSRP measure signal power from the specific sector and the unit of RSRP measurement is dBm. The standard values of the RSRP for different level of signal strength are shown in the table 5.

Table 5. Standard RSRP value range of LTE cellular signal [36].

RSRP	**Signal strength**	**Description**
≥-80 dBm	Excellent	Strong signal with maximum data speed.
-80 dBm to -90 dBm	Good	Strong signal with good data speed.
-90 dBm to -100 dBm	Fair-to-poor	Fluctuation in reliable data connection.
≤-100 dBm	No signal	Very poor or disconnection.

4.1.2 RSRQ

RSRQ measures signal quality of LTE cellular networks. RSRQ provides additional information when RSRP is not sufficient to make a reliable handover or cell re-selection decision [36]. The signal with high RSRQ is good even RSRP value is low. RSRQ depends on serving cell power and the number of transmit antennas. The value of RSRQ is given in dB and the range of RSRQ is defined from -3 dB (good) to -19 dB (bad). The standard values of the RSRQ for different level of signal strength are shown in the table 6.

Table 6. Standard RSRQ value range of LTE cellular signal [36].

RSRQ	**Signal Quality**	**Description**
$\geq$ -10 dB	Excellent	Strong signal with maximum data speed.
-10 dB to -15 dB	Good	Strong signal with good data speed.
-15 dB to -20 dB	Fair-to-poor	Connection connection.
$\leq$ -20 dB	No signal	very poor or Disconnection.

4.1.3 RSSI

RSSI is an estimated measure of power level that RF receiving device is receiving from an access point after possible attenuation at the antenna and the cable [37]. RSSI measures the quality of the signal that is received on the device. The received signal is stronger for higher values of RSSI. RSSI is measured in dBm since it is the measure of power. The range of RSSI value for RF signal depends on the sensitivity of the receiving device. The standard signal strength value of RSSI and their signal quality is summarized in the table 7.

Table 7. Standard RSSI value range of LTE cellular signal [37].

Signal strength (dBm)	**Rating**
-30 dBm	Amazing.
-67 dBm	Very good.
-70 dBm	Okay.
-80 dBm	Not good.
-90 dBm	Unusable.

4.1.4 SINR

SINR is defined as the ratio of signal power to interference plus noise power. The SINR defines signal quality [38] and the signal with less interference and noise power in combination is stronger than the signal with high interference and noise power. The SINR is often expressed in dB. The table 8 summarises the signal quality with respect to signal power [39].

Table 8. Standard SINR quality range of LTE cellular signal.

Signal strength (dB)	**Rating**
$\geq$ 20 dB	Excellent.
13 to 20 dB	Good.
0 to 13 dB	Okay.
$\leq$ 0	Not good.

4.2 Devices used for measurement

There are several network devices, cables and software applications that were used for the measurements purpose and they are listed and described below.

4.2.1 Log-periodic antenna

The log-periodic antenna is the wideband directional antenna that is capable of providing high directivity and gain. The antenna used in the measurement is LDPA model number DBDS-698-4000-14. It is designed to operate at all 4G frequencies and at 3.5 GHz frequency in 5G [21]. In the measurement, two similar log periodic antennas are mounted on the mast forming MIMO configuration for better signal reception. The two directional antennas are organized in cross polarization pattern. In cross polarization pattern, one signal is tilted at 45 degrees to the left and other at 45 degrees to the right, thus reducing the interference between antennas to minimum. This cross polarization configuration is done to increase the speed of the RF signal. The antennas separation is 45 cm as shown in the figure 12. The electrical and mechanical specification of LDPA antenna is given in the table 9.

Figure 12. Log-periodic antenna in the MIMO configuration.

Table 9. Specification of LDPA antenna used in the measurement [21].

Electrical specification			
Frequency range, MHz	698 – 960	1710 – 2700	3300 – 4000
Gain	12	14	10
VSWR	≤ 2.5	≤ 1.8	≤ 2.0

Mechanical specification	
Connector	N-Female
Operating temperature	-40 to +60 Celcius

For maximum power transfer to the antenna, the impedance should be perfectly matched. According to specification in the table 9, for band 20 frequency, VSWR is less than and equal to 2.5 and the gain given by the antenna is 12 dB.

4.2.2 ZTE 5G CPE MC801A Wi-Fi 6 Router

The device ZTE MC801A is a 4G/5G cellular modem integrated with the wi-fi router. It supports latest wi-fi access technology and allows multiple users to access the network at the same time. The router ZTE MC801A as shown in the figure 13 supports both 4G and 5G standards and enables users to enjoy ultra-fast 4G/5G networks including immersive streaming, gaming etc. The device provides high speed and low latency internet service with dual mode wi-fi 2.4 GHz and 5 GHz with the high gain omnidirectional antenna ensuring CPE connection at different angles. The device has

9 dBi directional antenna which can cover long distance in remote areas far away from the base station [40]. The other specifications of the router are mentioned in the table 10.

Figure 13. ZTE 5G MC-801A wi-fi router used for measurement.

Table 10. ZTE 5G CPE MC801A device specification [40].

Description	**Rating**
Network frequencies	5G(GHz): 3.5. 4G(MHz): 2100, 1800, 2600, 900, 800, 700, 2600.
Bandwidth	100 MHz.
Download rate	2.8 Gbps.
Support mode	Non-stand alone (NSA).
Operating tempreature	-22 to 50 °C.
Connection	2 x 1Gb LAN port 2 x antenna connector USB-C (not used) 1 x 1 RJ11 port.
Sim card	nano-sim.
Antenna	Two, TS-9 connectors.

4.2.3 Inductive coupler

The inductive coupler is a device that couples to a cell phone and diverts the signal from a booster antenna thereby ensuring better signal reception [41]. The inductive adapter shown in the figure 14 is compatible with 2G, 3G and 4G technology. It is a handy device which increases connectivity stability. The adapter consists of 50 cm cable (RG 174) that terminates in a SMA female connector. The electrical and mechanical specification of the device are given in the table 11.

Figure 14. Inductive adapter used for measurement.

Table 11. Electrical specification of adaptive coupling [41].

Frequency band	698 - 960 MHz 1710 - 2700 MHz.
VSWR (coupled and free space)	≤3:1.
Coax cable losses	0.78 dB/m @ 700 MHz 0.92 dB/m @ 900 MHz 1.35 dB/m @ 1800 MHz 1.6 dB/m @ 2400 MHz
Coupling loss @ 800 MHz	approximately -4 dB.
Tempreature range	-20 to +50 °C.

4.3 Cables used for measurement

Two sets of the coaxial cable are used for the measurements which are described below.

4.3.1 Antenna cable

The antenna cable is a cable that connects antenna to adaptive coupler or the adapter cable. The cable is low loss LMR 195 cable which is 1.5 m long and ends with SMA male connector at both ends. The measured loss in this cable was 1.3 dB.

4.3.2 STK-01 adapter cable

The STK-01 adapter cable also called adapter cable SMA/TS9 connects 4G/5G antenna to the router. This adapter cable completes the antenna connection to the router. The cable is 20 cm long and the ends of the cable are SMA female connector and the TS9 male connector. This cable is compatible with 4G and 5G routers [42].

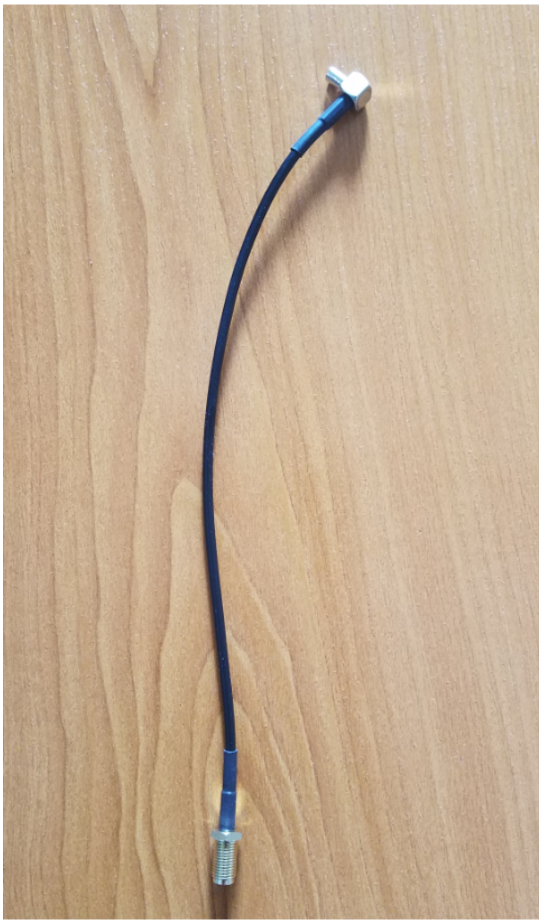

Figure 15. SKT-01 adapter cable.

4.4 Signal operator

The signal measurements were carried with two signal operators namely DNA and Elisa. DNA and Elisa are Finnish telecommunication group that provides cellular services to their customers throughout the country. For our measurement purpose, we decided to measure the RF connectivity in remote places using DNA and Elisa sim-cards and its base-station around the spot for the measurement. The Elisa sim-cards are used in cell-phones and DNA sim-card is used in the modem for signal measurement.

4.5 Cell phones applications

Mobile applications are the software application program designed to run on mobile devices for specific use. For our measurement purpose, we used several mobile applications which are listed below.

4.5.1 CellMapper

CellMapper is a software application that is used to locate cellular base stations in any geographical area. This application also shows the cell and base station identity number, the frequency of operation, the beam coverage area etc of that base station based on the network information [43]. It is available as a web page for desktops and as application for cell phones. In our measurement, we used CellMapper to locate base stations and get their identification number from the site of measurement.

4.5.2 NetMonster

NetMonster is an android networking application which shows the information related to the cellular network. It reports the cell ID and signal parameters RSSI, RSRP, RSRQ and SNR. This application also supports the map to find the location of the base station [44]. The version used for the data measurement is 2.18.5.

4.5.3 Signal Strength

Signal Strength is another software application designed to test the data rate and strength of cellular network. It is advanced software that has feature of displaying the signal strength of RF signal including its frequency range, channel identification and others. The application Signal Strength version used for the measurement is 24.1.2 [45].

4.5.4 Speedtest application

Speedtest is an android application which allows us to test our internet data rate at any time. This application allows user to ping the network and determine the upload and download speed of any network precisely. It features include test network speed, produce results, generate map data of cellular network and VPN connection [46].

4.6 Signal spectrum analyser

The signal spectrum analyser is a measurement device that intakes a RF signal and produces the signal plot in the frequency domain. The device measures the amplitude of an input signal against frequency within the full range of the instrument to see an effective insight to RF performance of the measured spectrum. The use of this device is to measure power of all the known and the unknown RF signal [47].

5 MEASUREMENT

The purpose of the thesis is to conduct measurement of LTE cellular signal at frequency 800 MHz using the devices illustrated in chapter 2 use cases and analyse improvement in signal strength in remote locations where only band 20 LTE signal is available. The other objectives are to observe how much gain these devices give in terms of signal parameters which are RSSI, RSRP, RSRQ and SNR. The weak signal strength at remote locations can be improved by adopting certain signal booster devices.

5.0.1 Measurement of s-parameter with VNA

VNA performs two types of measurements i.e, transmission and reflection. In transmission measurement, VNA stimulus signal is passed through the device under test and the passed signal is measured by VNA receivers on other side. The commonly used transmission s-parameter are the input port voltage reflection coefficient (S11), reverse voltage gain (S12), forward voltage gain (S21) and output port voltage reflection coefficient (S22). In this thesis work, S11 parameter is used to measure the loss of the antenna cable for its entire length. The used low antenna cable is LMR 195 and the loss of the cable measured is 1.3 dB as shown in the figure 16.

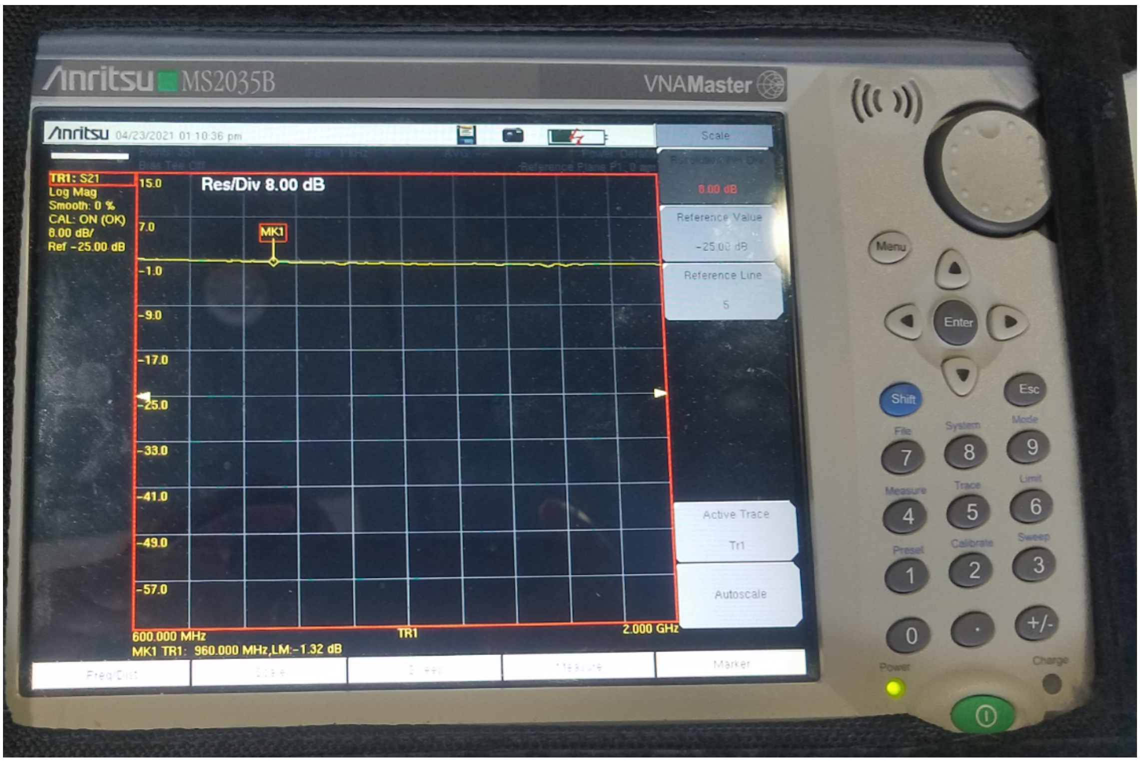

Figure 16. Antenna cable loss measurement.

5.1 Field measurement

The field measurements were conducted away from the city area of Oulu. The locations chosen were Sanginjoki and Kalimeenlampi areas in Loppula and Rokua. Loppula is approximately 27 km away in the east direction and Rokua is approximately 70 km in the east-south direction from the University of Oulu. The LTE signal with the band 20 and frequency 800 MHz were available at the sites. Two signal booster devices were used for measurement at the sites. They were adaptive coupler and the MC801A CPE 4G/5G modem with the integrated router. Aslo the measurements were recorded on user equipment (UE) using software applications. The UE were three cell phones 1, 2 and 3. The inductive coupler measurements have three cases i) cell phones measurement without use of the adapter at height 1.4m ii) cell phones measurement with the adapter at antenna height 1.4 m and iii) cell phones measurement with the adapter when the antenna is raised to height 3.5 m. The measurement procedure and findings are described below.

5.1.1 Adaptive coupler measurement at Loppula

In the first step of measurement series of RF signal, we installed the directional antenna on the mast and pointed the antenna toward the Elisa base station. The location of measurement with base station and antenna location is shown in the figure 17.

Figure 17. Location of first inductive coupling measurement.

Figure 18. First inductive coupling measurement with antenna height raised to 3.5 m.

Figure 19. First inductive coupling measurement with antenna height at 1.4 m.

The antenna is connected with the antenna cable and the inductive coupler. Cell phone is put against the inductive coupler and the readings are recorded. This data recording setup is shown in the figure 18. The base station identification is eNB ID 8371 and measurement is done for the LTE frequency band 20. The recorded data are show in the table 12.

Table 12. First inductive coupling measurement data with mobile devices 1, 2 and 3.

Device 1 measurement data				
Mobile device position	**RSSI**	**RSRP**	**RSRQ**	**SNR**
Device reading without adapter	-113	-97	-6	7
Device reading with adapter	-113	-96	-4	5
Device reading with antenna raised at 3.5 m height	-113	-100	-5	5
Device 2 measurement data				
Device reading without adapter	-77	-102	-10	7.6
Device reading with adapter	-67,-69	-95,-96	-7	12
Device reading with antenna raised at 3.5 m height	-75	-101, -103	-10	10
Device 3 measurement data				
Device reading without adapter	-79	-108	-12	16
Device reading with adapter	-65	-89	-7	12.6
Device reading with antenna raised at 3.5 m height	-71,-75	-102	-9	5

The second measurement is done at some distance apart from first site location in Loppula. The second measurement site is shown in the figure 20 and the measured data with the inductive coupling is shown in the table 13.

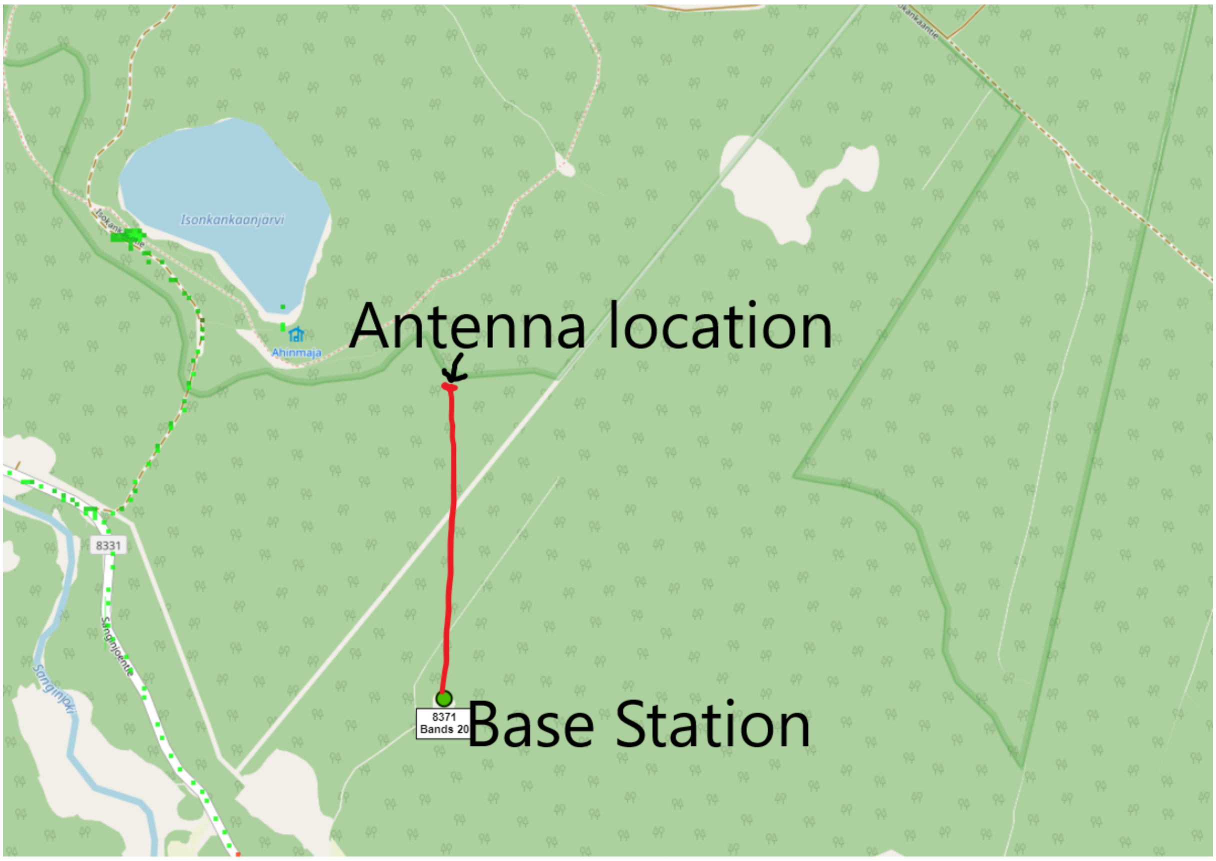

Figure 20. Second inductive coupling measurement at Loppula.

Table 13. Second inductive coupling measurement data with mobile devices 1, 2 and 3.

Device 1 measurement data				
Mobile device position	**RSSI**	**RSRP**	**RSRQ**	**SNR**
Device reading without adapter	-113	-97	-9	10
Device reading with adapter	-113	-93,-98	-6,-9	6,11
Device reading with antenna raised at 3.5 m height	-113	-89	-9	7
Device 2 measurement data				
Device reading without adapter	-71,-73,-75	-101	-8	6.2,8.4,9.6
Device reading with adapter	-69,-71	-98	-8	8
Device reading with antenna raised at 3.5 m height	-65,-67	-93	-10	14
Device 3 measurement data				
Device reading without adapter	-71	-96	-8	12.6
Device reading with adapter	-63	-89	-8	12.2
Device reading with antenna raised at 3.5 m height	-76	-94	-7	8.6

5.1.2 Adaptive coupler measurement at Rokua

The third set of measurement was carried out at Rokua where the geography is hilly. The data measurements were conducted uphill and downhill. The measurements were also conducted indoor in a cottage which is on the bank of the lake, below a hill. The measurement has three cases, first data measurement without the inductive coupler, second with the inductive coupler and third data measurement with the inductive coupler but at the antenna raised at 3.5 m height. The base station ID is 8929 and measurement location is shown in the figure 21.

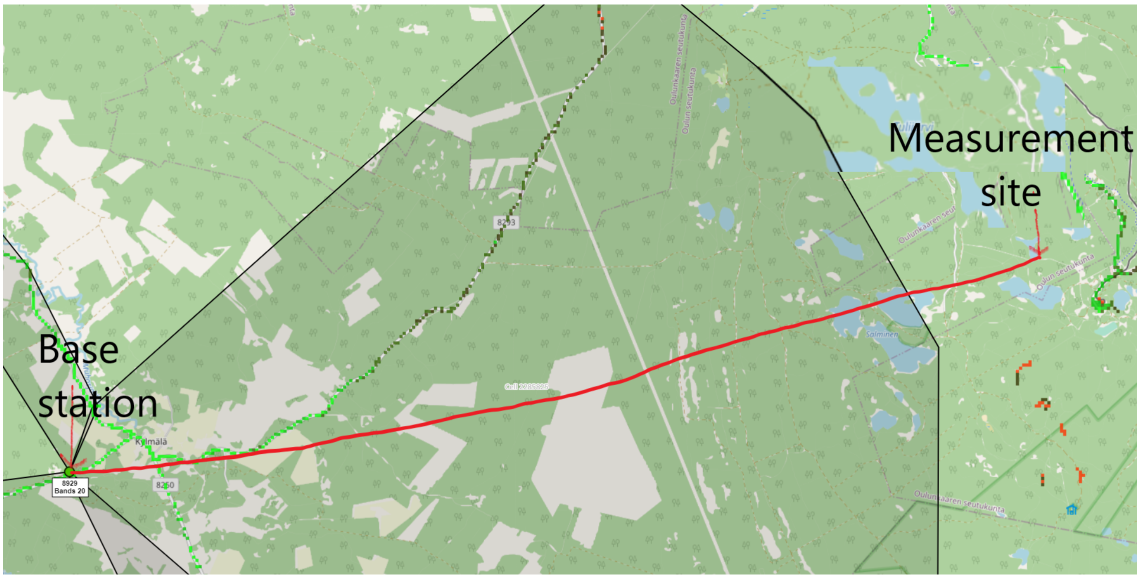

Figure 21. Base station location of third measurement.

Figure 22. Location site of third measurement downhill at Rokua.

At this site, the inductive coupling measurements with three different cell phone devices were done and the data were recorded as presented in the table 14.

Table 14. Inductive coupling measurement data downhill with mobile devices 1, 2 and 3.

Device 1 measurement data				
Mobile device position	**RSSI**	**RSRP**	**RSRQ**	**SNR**
Device reading without adapter	-113	-109	-8	4
Device reading with adapter	-113	-105	-9	5
Device reading with antenna raised at 3.5 m height	-113	-109	-13, -10	3.6
Device 2 measurement data				
Device reading without adapter	-85	-113	-10	14
Device reading with adapter	-81	-111	-11	3.4, 8
Device reading with antenna raised at 3.5 m height	-79	-105	-8	8.4
Device 3 measurement data				
Device reading without adapter	-85	-115	-8	5, 6
Device reading with adapter	-87	-117	-9	5
Device reading with antenna raised at 3.5 m height	-75	-103	-9	7, 8

The inductive coupling and data rate measurements were also conducted uphill to observe the signal parameters qualities. The measured data is presented in the table 15 and 16.

Table 15. Inductive coupling measurement data uphill with mobile devices 1, 2 and 3.

Device 1 measurement data				
Mobile device position	**RSSI**	**RSRP**	**RSRQ**	**SNR**
Device reading without adapter	-113	-105	-8	5
Device reading with adapter	-113	-105	-9	6
Device reading with antenna raised at 3.5 m height	-113	-102	-7	7
Device 2 measurement data				
Device reading without adapter	-77	-103	-9	5.6
Device reading with adapter	-77	-105	-9	3.8
Device reading with antenna raised at 3.5 m height	-77	-104	-12	5.6
Device 3 measurement data				
Device reading without adapter	-81	-109	-9	5
Device reading with adapter	-77	-104	-9	4.4
Device reading with antenna raised at 3.5 m height	-73	-99	-8	9.2

Table 16. Speed test uphill on devices 1 and 2.

Speed test on devices 1 in Mbps		
Device position	**Download speed**	**Upload speed**
Without inductive coupling	12	1.5
With inductive coupling	16.9	1.5
Speed test on device 2 in Mbps		
Without inductive coupling	13.6	0.8
With inductive coupling	9.9	0.46

5.1.3 Data rate measurement using MC801A CPE 5G modem

The data rate measurements were carried out in a cottage in Rokua. The devices used were MC801A modem and UE. The UE measured data rate using the Speedtest software application. First, the UE measured the data rate from its signal operator. Second, the UE measured wi-fi data rate released through modem. The measured data is categorised into two groups namely indoor and outdoor. The signal strength illustrated by the MC801A was -110 dBm and data rates measured by UE are presented in the table 17.

Table 17. Data rate test using MC801A CPE 5G modem.

Speed test in Mbps		
Data rate measurement	**Download speed**	**Upload speed**
Data rate outside cottage without modem	2.67	0.35
Data rate inside cottage downstairs without modem	13.14	3.97
Data rate inside cottage downstairs with modem	23	4.5
Data rate inside cottage upstairs without modem	3.7	0.1
Data rate inside cottage upstairs with modem	32.8	10

6 RESULT ANALYSIS

The adaptive coupling measurements were conducted on the Elisa cellular network operator with three different cell phone devices. The data rate measurements were carried out on DNA network operator with modem. The results analysis is described in the paragraph below.

6.1 Adaptive coupling measurement at Loppula

The table 12 shows first measurement data at Loppula using three different cell phones with the inductive coupler. The measured data have various values of signal parameters for the different antenna position. For device 1, RSSI value is -113 dBm which is in unstable range, RSRP value is in fair-to-poor range, RSRQ is excellent and SNR is in weak range. Similarly, the device 2 and 3 have very good RSSI, fair-to-poor RSRP, good RSRQ and SNR value. The device 1 measurement with the adapter use at height 1.4 m is better for RSRP and RSRQ than without the use of the adapter at the same height. When the antenna is raised at height 3.5 m, the inductive coupler reading for signal parameters are similar to coupler reading with the adapter at height 1.4 m. Device 1, has better performance with the adaptive coupling than without coupling. Device 2 has improved performance with the adapter over without use of the adapter at height 1.4 m. With adapter use, the highest improvement in RSSI, RSRP, RSRQ and SNR is by 10 dB, 7 dB, 3 dB and 4.4 dB respectively. Device 2 at height 3.5 m shows the degraded performance compared with height 1.4 m with the adapter except improvement in RSRQ value by 3 dB. The device 3 with the adapter at height 1.4 m has higher improvement for signal parameters RSSI, RSRP and RSRQ is by 14 dB, 19 dB and 5 dB respectively over without adapter reading over the same height except SNR value. When the antenna for this device is raised to 3.5 m, the overall signal parameters are degraded. From this table, the gist can be drawn that adapter performance at height 1.4 m is better than two other cases.

The table 13 shows the readings of the performance of three cell phones devices at second location in Loppula. Device 1 reading for RSSI is the same for all three cases of mobile device position. The device 1 measurement with the adapter at height 1.4 m is better for RSRP, RSRQ and SNR parameters by 4 dB, 3 dB and 1 dB at maximum respectively despite some variation. Device 1 reading without the adapter at height 1.4 m is poor for all four signal parameters. When the antenna is raised at height 3.5 m the device 1 with the adapter, only RSRP reading is improved by 9 dB compared with RSRP value at height 1.4 m. Similarly, the device 2 with the adapter at height 1.4 m has better signal parameters reading compared without the adapter at the same height. The improvement of 6 dB and 3 dB were seen for RSSI and RSRP respectively. If the antenna is raised by 3.5 m from 1.4 m, the improvements were 10 dB and 8 dB for RSSI and RSRP respectively except for RSRQ and SNR. The device 3 performance with the adapter at height 1.4 m is better for RSSI and RSRP compared with the device without the adapter at the same height. When the height of the antenna is raised to 3.5 m, the device 3 with the adapter has poor performance compared with the device without the adapter except for improvement in RSRP value by 2 dB. Overall, the devices 1, 2 and 3 shows better performance with the adapter at height 1.4 m. There is slight improvement when the height of the antenna is raised to 3.5 m.

On the basis of the measurements data at both sites in Loppula, the cell phone devices with the inductive coupler at the antenna height 1.4 m and 3.5 m have signal improvement than without its use. The performance with the inductive coupler at the antenna height 1.4 m was better than the antenna height at 3.5 m. This result can also be attributed to the short length of the antenna cable. The antenna positioned higher requires longer cable and the longer cable has higher signal loss. The electric cable above the measurement site in Loppula has effect on the data measurement. With the inductive coupler at the antenna height 1.4 m, the maximum signal improvements were 14 dB for RSSI, 19 dB for RSRP, 5 dB for RSRQ and 4.4 dB for SNR compared without the inductive coupler use. The signal improvements at the antenna height 3.5 m are 4 dB for RSSI, 5 dB for RSRP, 1 dB for RSRQ and 6 dB for SNR at maximum over the antenna height at 1.4 m with inductive coupler use. These improvements are quite small but positive. Thus the device inductive coupler has signal improvement performance and is beneficial.

6.2 Adaptive coupling measurement at Rokua

The table 14 shows the data measurement using cell phones at downhill in Rokua. The device 1 has the same value for RSSI for all three mobile device positions. While there is improvement in the signal performance for the device with the adapter at the antenna height 1.4 m for RSRP, RSRQ and SNR by 4 dB, 1 dB and 1 dB respectively compared without use of the adapter. When antenna height is raised by 3.5 m, the device with the adapter shows improvement in RSRQ value by 5 dB at maximum compared with the device without the adapter at height 1.4 m. Device 2 with the adapter has better performance when the antenna is raised to height 3.5 m. The device 2 reading for RSSI, RSRP and SNR is improved by 6 dB, 8 dB and 5.6 dB respectively over the device reading without the adapter at the antenna height 1.4 m. Device 2 with the adapter at the antenna height 1.4 m also shows signal improvement over device 2 without the adapter at the same height but this is less than the reading when the antenna is at height 3.5 m. The device 3 also follows the pattern of device 2 performance. The device 3 with adapter reading when the antenna height is at 3.5 m is superior than the other two cases. In this table, the cell phone devices performance downhill is better with the adapter when the antenna is raised to height 3.5 m.

The table 15 shows the performance of the cell phone devices at the uphill position. The device 1 as usual has the same value for RSSI at -113 dBm which is the poor signal. The device 1 with the adapter has better performance when the antenna is raised to the height 3.5 m uphill. The value for RSRP, RSRQ and SNR is better by 3 dB, 2 dB and 2 dB respectively at maximum. Device 2, too has the same value for RSSI at -77 dBm for all three mobile devices position. The RSSI signal rating is weak at this value. Device 2 with the adapter at antenna height 3.5 m and device 2 without the adapter at height 1.4 m have similar reading for RSRP and SNR but RSRQ value is higher for device 2 with the adapter at antenna height 3.5 m. The device 3 with the adapter when the antenna is raised at 3.5 m, the overall signal parameters performance is better. The RSSI, RSRP, RSRQ and SNR values are improved by 8 dB, 10 dB, 1 dB and 4.8 respectively at maximum. In nutshell, the cell phone devices performance with the adapter at antenna height 1.4m is high but devices with the adapter at the antenna height 3.5 m are even higher.

The table 16 shows the speed test of the cellular signal at uphill location from devices 1 and 2. The device 1 has higher download speed with inductive coupling compared without the coupling use. The download speed is increased by 4.9 Mbps. But, the upload speed remain the same at 1.5 Mbps with or without coupling. On the contrary, the device 2 shows lower download and upload speed with coupling and higher download and upload speed without coupling.

The cell phone devices with the adapter at Rokua performed better when the antenna height was raised at 3.5 m. The performance of the inductive coupler with device 3 was better uphill at the antenna height raised to 3.5 m compared with the downhill antenna positions. The uphill signal improvements were 2 dB for RSSI, 4 dB for RSRP, 1 dB for RSRQ and 2.2 dB for SNR over downhill readings. This is positive response and relevant to the directional antenna principle. As we raise the height of the antenna, the obstacles are less and the chances of signals at LoS path are higher. The maximum differences between the uphill and downhill measurements for RSSI, RSRP and RSRQ were 2 dB, 4 dB and 1 dB respectively. The uphill signal readings were better to the downhill readings. On the basis of the performance comparison at both locations, we strongly suggest the use of the adapter is beneficial for signal improvement at remote locations.

6.3 MC801A CPE 4G/5G modem measurement at Rokua

The table 17 illustrates the indoor and the outdoor speed test with MC801A 4G/5G modem and the UE at the cottage in Rokua. The speed tests are conducted outside the cottage, inside downstairs and inside upstairs in the cottage. The data rate measured with the UE outside the cottage is lowest. The data rates are 2.67 Mbps for download and 0.35 Mbps for upload. Inside the cottage downstairs, the data rate for download and upload with use of the modem are higher compared without use of the modem. The increment of speed for download and upload are 9.86 Mbps and 0.53 Mbps respectively. Similarly, the data rates upstairs inside the cottage with the modem are also higher than without use of the modem. The download and the upload speed measured using the modem are 32.8 Mbps and 10 Mbps respectively. This is an improvement of 21.9 Mbps for the download speed and 9.9 Mbps for the upload speed. In both cases, the data rates with the modem are higher.

The use of MC801A CPE 4G/5G modem has very promising results on enhancing signal strength at remote location for indoor application. The measurement data in the table 17 clearly shows that the modem increased the upload and download speed when it is placed at up the stair inside cottage. Based on this fact, we would highly recommend that this device is highly useful for indoor application in enhancing internet connectivity speed at remote locations. The modem on the other hand with the external antenna connection which did not produce any beneficial result. we suspect the antenna ports were unresponsive due to lack of software update.

7 DISCUSSION

In first and second data set measurements at Loppula, the performance of cell phone devices with the adapter at the antenna height 1.4 m were impressive in comparison with the data measurement without the adapter at the same height. The maximum improvements in the readings were 14 dB for RSSI, 19 dB for RSRP, 5 dB for RSRQ and 4.4 dB for SNR. These outcomes were expected because of inductive coupler device use. The device is designed to provide positive gain. The adapter device when coupled with cell phones and the antenna raised to the height 3.5 m did not perform as expected. At this height, the signal should have higher strength compared with the signal at height 1.4 m. The variation in the signal is common and the unexpected results might be caused by the signal attenuation by the trees or by the reflection. Also the effect of the additional antenna cable cannot be ignored.

The overall performance of the inductive coupler at downhill and uphill at Rokua were quite similar when the antenna height was raised to 3.5 m. The maximum downhill improvements in the reading were 10 dB for RSSI, 12 dB for RSRP, 2 dB for RSRQ and 3 dB for SNR. Similarly, the maximum improvements to the uphill measurement were 8 dB for RSSI, 10 dB for RSRP, 1 dB for RSRQ and 4.2 dB for SNR. At Rokua, the signal variations were smaller and the inductive coupler provided better gain compared with gain obtained at Loppula. These results are as expected because in general we know that if the directional antenna is raised to certain height, it is able to absorb the weak signal, boost it and then feed the connected device with enhanced signal strength. Thus, the inductive coupler provides benefit.

The speed test with cell phone device 1 showed the expected result while device 2 showed the opposite result. The speed tests with the device 1 increased download speed by 4.9 Mbps after inductive coupling use. The upload speed was the same with and without inductive coupling use. On the other hand, the download and upload speed were decreased by 3.7 Mbps and 0.34 Mbps respectively on the device 2 after inductive coupling test. This was unexpected. Different cell phones have the different level of signal absorbing capacity. The positioning of the UE to the inductive coupling has its impact too. The sensitivity of the UE to signal also varies. Signal level is changing every time and the varying signal might have caused the unexpected speed results.

The performance of MC801A modem was amazing for the indoor application. Inside the cottage, the UE was not able to connect to 4G. The UE was connected mostly to 3G. After the modem connection, 4G connection was visual on the UE. The modem raised both the download and the upload data rate. The maximum increments in the data rates were recorded upstairs inside the cottage. With this modem, the data rate increments were 21.9 Mbps and 9.9 Mbps for download and upload respectively compared without use of the modem at upstairs.

The main intention of the measurement was to incorporate specific measurement software i.e Nemo Outdoor to couple with the 5G modem and measure the signal parameters of both 4G LTE and 5G networks. However, the current version of the software was found to be incompatible with the modem and the plan has to be dropped. This limited our measurement performance. Other limitation factor was that the modem device did not work with the external antenna connection. Despite the router had external antenna connection ports, the router was unresponsive to the antenna connection. If the router had responded to the external antenna connection, the result would have been interesting to see and analyse.

8 CONCLUSION

The complex terrain and natural barriers in the remote areas make cellular connectivity strength comparatively low. The signal strengths at these locations are attenuated by these factors. Hence, the quality of communication and the internet connectivity in these areas are quite problematic. But the poor connectivity at the remote places, for the indoor and outdoor applications can be upgraded by installing certain network devices. The objective of this thesis were to install such network devices at remote locations and then perform the measurement and witness if these devices provide boost to the cellular signal. The practical setups of signal connectivity were made at remote locations and performance measurements were recorded. The signal booster devices were the inductive adapter and the 4G/5G cellular modem with the integrated router. Although the signal had variation in the signal level, the devices were able to produce the positive gain in the remote locations where only LTE signal band 20 was available at frequency 800 MHz. The inductive coupler improved signal connectivity when it was attached with cell phones and the antenna raised at height 1.4m and 3.5m. The MC801A modem increased signal connectivity speed for indoor application. Hence, these devices are found beneficial for upgrading the remote connection.

9 REFERENCES

[1] Singh R.D. (2012) Wireless for communities: Empowering communities through wireless connectivity. IEEE Internet Computing 16, pp. 77–79.

[2] Cavalcante A.M., Marquezini M.V., Mendes L. & Moreno C.S. (2021) 5g for remote areas: Challenges, opportunities and business modeling for brazil. IEEE Access 9, pp. 10829–10843.

[3] Roslee M. & Last C.R. (2012) Wran system on zbc tv: A new way to internet connectivity for rural areas in zimbabwe. In: 2012 International Symposium on Telecommunication Technologies, pp. 168–174.

[4] Liang Y.C., Hoang A.T. & Chen H.H. (2008) Cognitive radio on tv bands: a new approach to provide wireless connectivity for rural areas. IEEE Wireless Communications 15, pp. 16–22.

[5] Yaacoub E. & Alouini M.S. (2020) A key 6g challenge and opportunity—connecting the base of the pyramid: A survey on rural connectivity. Proceedings of the IEEE 108, pp. 533–582.

[6] Nedevschi S., Surana S., Du B., Patra R., Brewer E., Stan V. & Telemobil Z. (2007) Potential of cdma450 for rural network connectivity. IEEE Communications Magazine 45, pp. 128–135.

[7] Khan M.M., Abbasi Q.H., Alomainy A. & Hao Y. (2011) Study of line of sight (los) and none line of sight (nlos) ultra wideband off-body radio propagation for body centric wireless communications in indoor. In: Proceedings of the 5th European Conference on Antennas and Propagation (EUCAP), pp. 110–114.

[8] Ardakani M.H., Heidarpour A.R. & Uysal M. (2015) Non-line-of-sight ultraviolet communications over atmospheric turbulence channels. In: 2015 4th International Workshop on Optical Wireless Communications (IWOW), pp. 55–59.

[9] Saunders S.R., Aragï A. et al. (2007) Antennas and propagation for wireless communication systems. John Wiley & Sons.

[10] Shi Q., Tröltzsch U. & Kanoun O. (2011) Analysis of the parameters of a lossy coaxial cable for cable fault location. In: Eighth International Multi-Conference on Systems, Signals Devices, pp. 1–6.

[11] SOLIDSIGNALBLOG (2021), How can i connect an antenna to my cell phone? URL: `https://cutt.ly/4x2L5rC`.

[12] Balanis C.A. (2005) Antenna theory: analysis and design. Wiley-Interscience.

[13] Bankey V. & Nella A. (2016) Design of a yagi-uda antenna with gain and bandwidth enhancement for wi-fi and wi-max applications. SSRN Electronic Journal .

[14] Kumar H. & Kumar G. (2017) Compact planar yagi-uda antenna with improved characteristics. In: 2017 11th European Conference on Antennas and Propagation (EUCAP), pp. 2008–2012.

[15] Reddy M. (2018) Directional yagi uda antenna for vhf applications. International Journal of Advancements in Technology 09.

[16] Oliner A., Knittel G., Agency U.A.A.B.M.D., Laboratory L., of Brooklyn. Electrophysics Dept P.I. & of Brooklyn. Dept. of Electrophysics P.I. (1972) Phased Array Antennas. Modern frontiers in applied science, Artech House. URL: `https://books.google.fi/books?id=agYoAQAAMAAJ`.

[17] Ochala I. & Okeme I. (2011) Design and implementation of a high-gain compound yagi antenna. In: Pelagia Research Library, pp. 2008–2012.

[18] Tutorialspoint (2021), Antenna theory - log-periodic antenna. URL: `https://bit.ly/3il6x8h`.

[19] Tse D. & Viswanath P. (2005) Fundamentals of Wireless Communication. Cambridge University Press.

[20] Kabiri Y., Borja A.L., Kelly J.R. & Xiao P. (2019) A technique for mimo antenna design with flexible element number and pattern diversity. IEEE Access 7, pp. 86157–86167.

[21] SatShop (2021), Sma male to sma female cable, cfd-200 / h155pe / sh-200 / hdf-195 / lmr-195, super low-loss, 6 mm, 0.5 m, black. URL: `https://bit.ly/3vFldlu`.

[22] Cable C.E.W.. (2021), Coaxial cable types. URL: `https://www.conwire.com/coaxial-cable-types/`.

[23] Hardesty G. (2020), Antenna cables: Definitions of components and terms. URL: `https://bit.ly/3dvqhTH`.

[24] Envision A. (2021), Understanding cable and antenna analysis. URL: `https://bit.ly/3bOwUzJ`.

[25] Solutions M.M.A. (2021), What is the cable loss for mobile mark antenna's cables? URL: `https://bit.ly/3tiMf1x`.

[26] Anritsu (2021), Understanding cable and antenna analysis. URL: `https://bit.ly/3cUvTX1`.

[27] Toppr (2021), Inductive reactance formula. URL: `https://bit.ly/3zEAEhl`.

[28] Components E. (2021), Active passive components - what is the difference between the two? URL: `https://bit.ly/3a1Tp3c`.

[29] Cenatiempo D. (2021), What is an antenna coupler? URL: `https://www.wisegeek.com/what-is-an-antenna-coupler.htm`.

[30] Matias R., Cunha B. & Martins R. (2013) Modeling inductive coupling for wireless power transfer to integrated circuits. In: 2013 IEEE Wireless Power Transfer (WPT), pp. 198–201.

[31] RFID4U (2021), Inductive and backscatter coupling. URL: `https://bit.ly/3jsU80A`.

[32] Yousuf M.A., Das T.K., Khallil M.E., Aziz N.A.A., Rana M.J. & Hossain S. (2021) Comparison study of inductive coupling and magnetic resonant coupling method for wireless power transmission of electric vehicles. In: 2021 2nd International Conference on Robotics, Electrical and Signal Processing Techniques (ICREST), pp. 737–741.

[33] Tekgun B., Sozer Y., Tsukerman I., Upadhyay P. & Englebretson S. (2019) Core loss estimation in electric machines with flux-controlled core loss tester. IEEE Transactions on Industry Applications 55, pp. 1299–1308.

[34] Abdolkhani A. (2016) Fundamentals of inductively coupled wireless power transfer systems. In: E. Coca (ed.) Wireless Power Transfer, IntechOpen, Rijeka, chap. 1. URL: https://doi.org/10.5772/63013.

[35] Roßkopf A., Bär E. & Joffe C. (2014) Influence of inner skin- and proximity effects on conduction in litz wires. IEEE Transactions on Power Electronics 29, pp. 5454–5461.

[36] TELTONIKA (2018), Rsrp and rsrq. URL: https://wiki.teltonika-networks.com/view/RSRP_and_RSRQ.

[37] CableFree (2021), Lte rssi, rsrp and rsrq measurement. URL: https://bit.ly/3ppxIjV.

[38] Hadj-Kacem I., Braham H. & Jemaa S.B. (2020) Sinr and rate distributions for downlink cellular networks. IEEE Transactions on Wireless Communications 19, pp. 4604–4616.

[39] TELTONICA (2018), Sinr. URL: https://wiki.teltonika-networks.com/view/SINR.

[40] ZTE (2019), Zte mc801a review. URL: https://www.4gltemall.com/blog/tag/zte-mc801a-review.

[41] Ltd P.A. (2020), Poynting making wireless happen. URL: https://bit.ly/3hC08oG.

[42] FINNSAT (2020), Adapters - adapter cable sma/ts9 20cm - finnsat. URL: https://www.sahkonumerot.fi/7419030.

[43] Cellmapper (2021), Cellmapper application. URL: https://bit.ly/3oMF6Fr.

[44] Mrocek M. (2021), Netmonster android application version 2.18.5. URL: https://netmonster.app/#.

[45] Strength S. (2021), Signalstrength application. URL: https://cutt.ly/Rnww5Jt.

[46] Apgar M. & Suttles D. (2019), Speedtest by ookla. URL: https://bit.ly/3vO9imp.

[47] TEKTRONIX (2020), Spectrum analyzer how-to guide: What they are, what they measure, how to use them. URL: https://bit.ly/3hwITFE.